MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS

7 March 2013

B. L. ("Les") Lee, ScD
AFOSR/RTD
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Report Documentation Page

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2013 AFOSR SPRING REVIEW
3002B PORTFOLIO OVERVIEW

NAME: ***B. L. ("Les") Lee***

BRIEF DESCRIPTION OF PORTFOLIO:

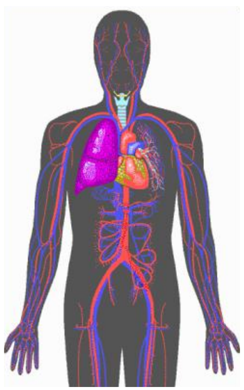
Basic science for integration of emerging materials and micro-devices into future Air Force systems requiring multi-functional design

LIST OF SUB-AREAS:

- ***Design of Autonomic/Self-Sustaining Systems;***
- ***Design of Reconfigurable Systems;***

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Self-Diagnosis;
Self-Healing, Remediation & Structural Regeneration;
Self-Cooling & Thermal/Irradiation Management;
Energy Transduction & System Integration;
Actuation, Morphing & Threat Neutralization;
Engineered Bio/Nano/Info-materials

AUTONOMIC RESPONSE



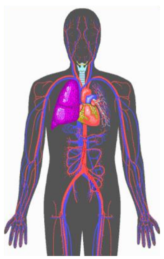
Autonomy:

The ability to function in an independent and automatic fashion

11

INSPIRED BY BIOLOGY…
Creating a Synthetic Autonomic System

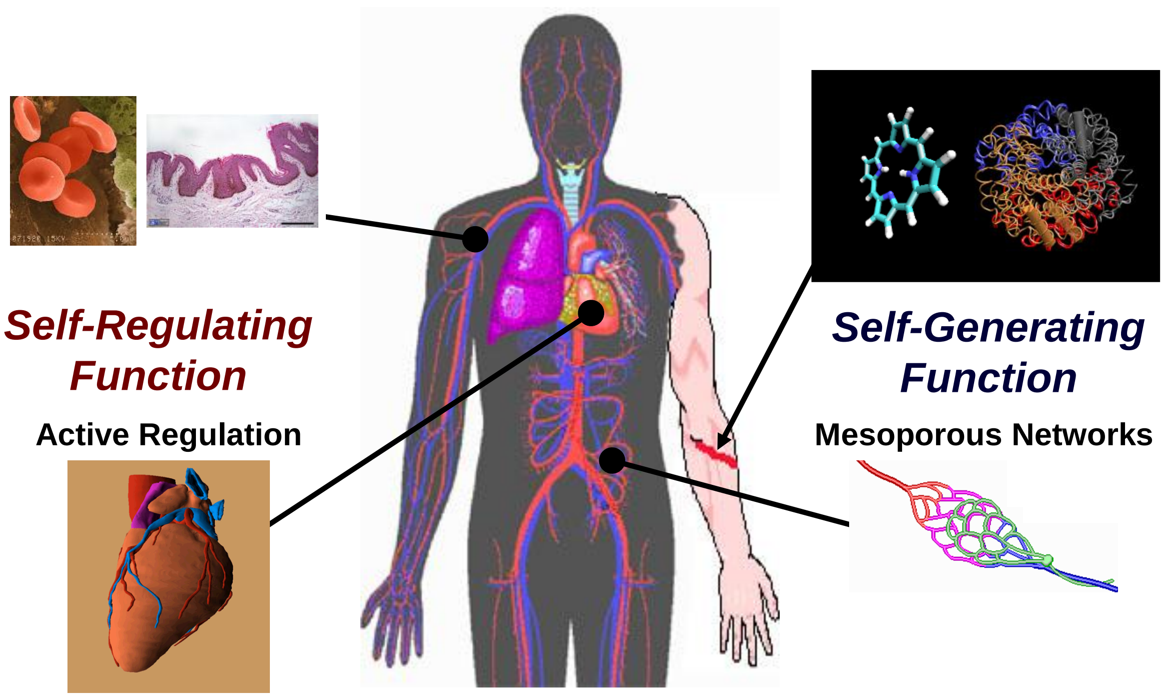
AUTONOMIC RESPONSE



Autonomy:

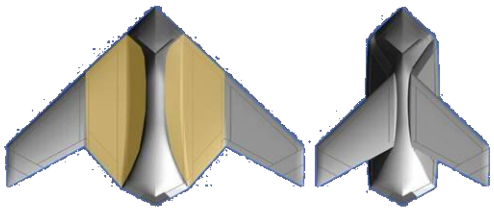
The ability to fun
independent and
fashion

FUNCTIONS OF INTEREST

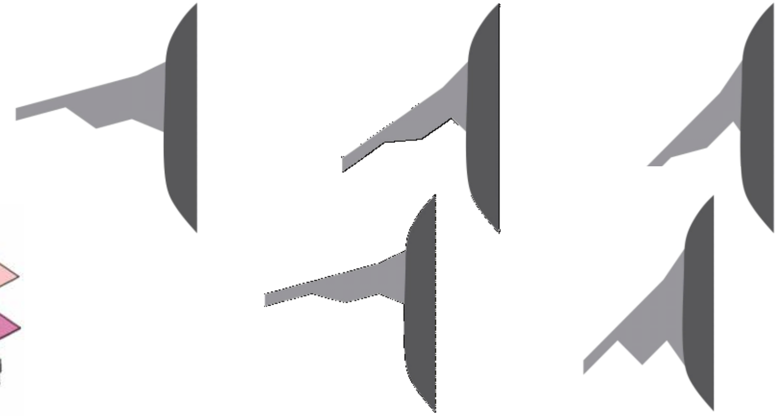


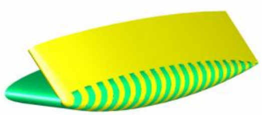
MORPHING AIRCRAFT

Source: AFRL/RB



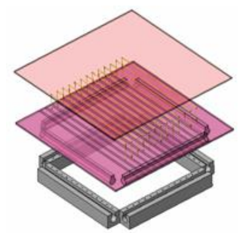
Concepts





Mechanization

Enablers



Flexible Skins

Adaptive Structures

Moving Beyond Swept Wing
Large Scale Area Changes
Showing It Can Be Done!

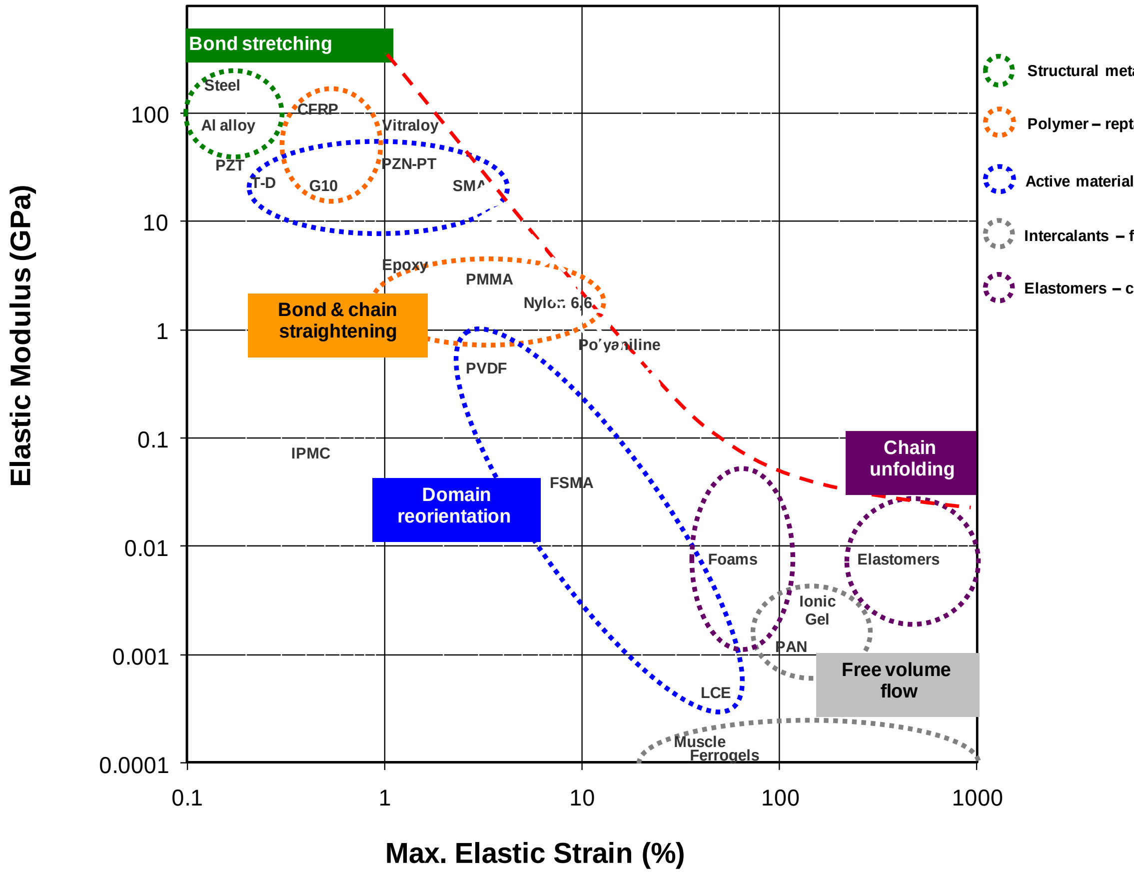
Wind Tunnel Tests

NASA 16 Ft Transonic Dynamics Tunnel

A First In Aviation History

ADAPTIVE STRUCTURES: *TECHNICAL CHALLENGES*

- **Structural materials are made to NOT deform,**
- **Those that deform by mechanization, add weight and complexity**
- **Reconfiguring is easy on land, but not air, under sea, or in space**
- **Structural materials made to deform on demand with minimized weight and complexity is a key technology.**



G. McKnight (HRL, Inc.)

Common materials cannot achieve simultaneous high stiffness and large deformation

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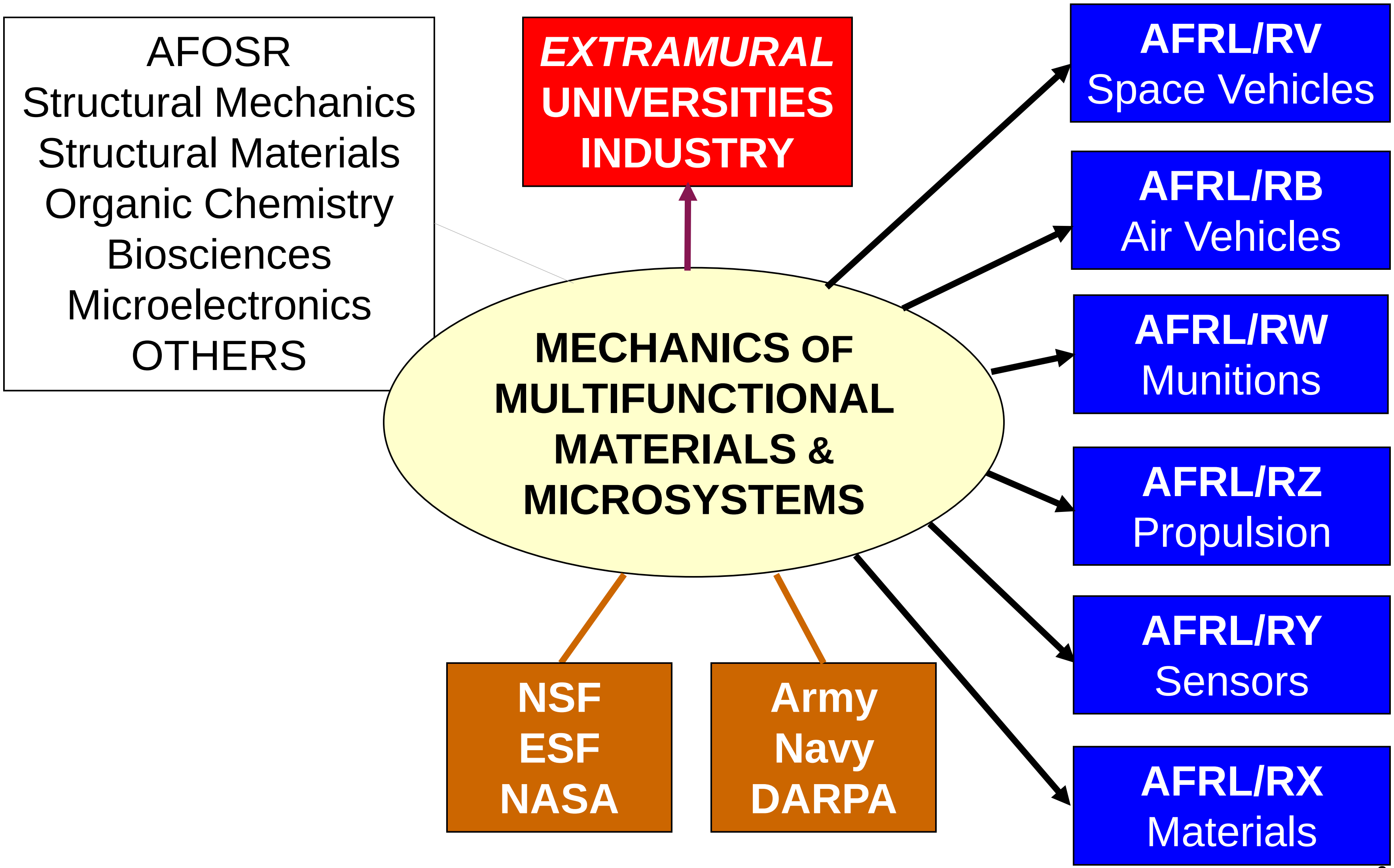

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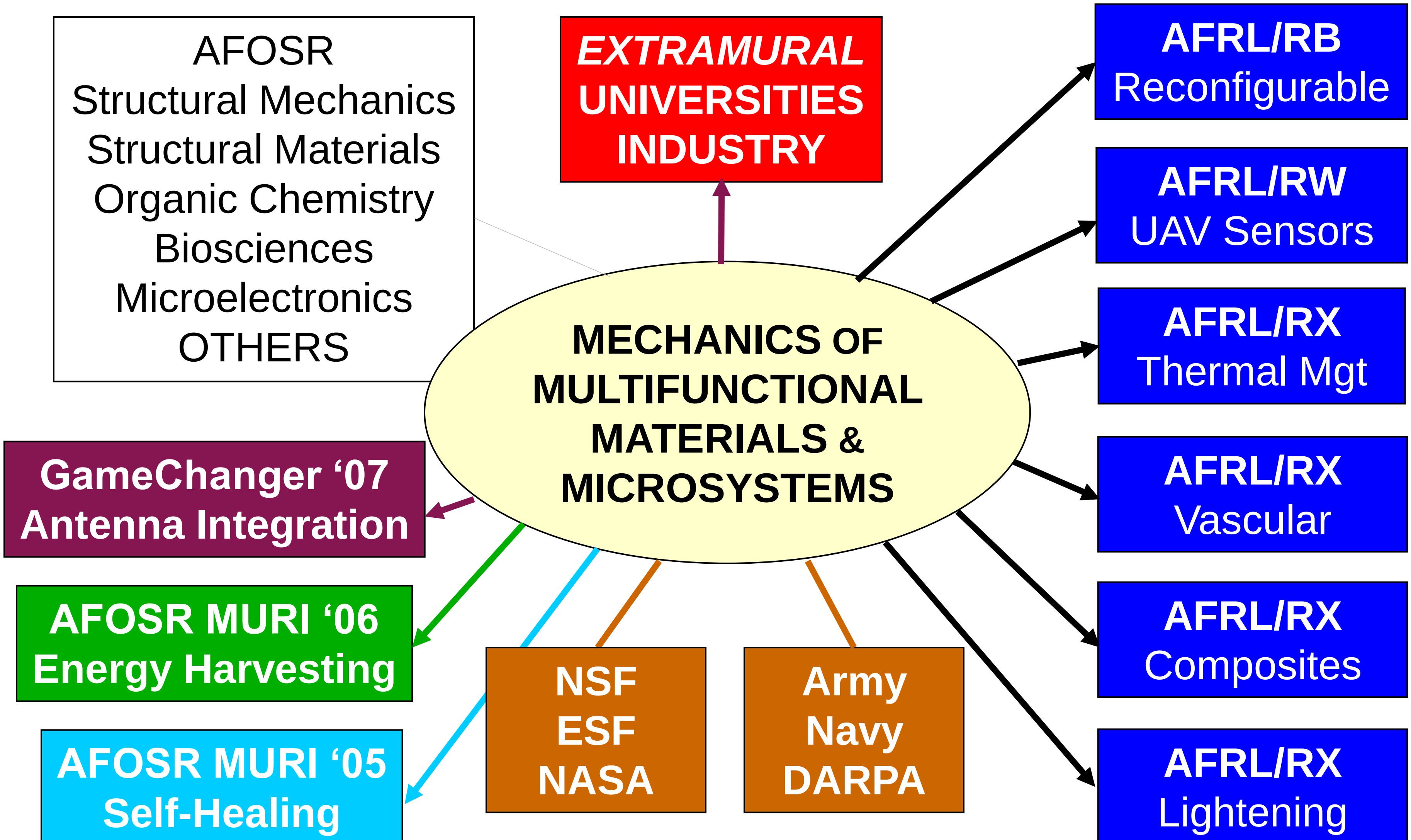

PROGRAM INTERACTION

AFOSR
Structural Mechanics
Structural Materials

MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS

EXTRAMURAL
UNIVERSITIES
INDUSTRY

AFOSR BRI '12
Biomolecules

AFOSR/RW CoE '12
High-Rate Physics

AFOSR MURI '09
Sensory Network

Discovery CT '09
Reconfigurable

Director's Call '09
Energy from Environ

NSF
ESF
NASA

Army
Navy
DARPA

AFLR/RB
Reconfigurable

AFRL/RW
UAV Sensors

AFRL/RX
Thermal Mgt

AFRL/RX
Active Polymer

AFRL/RX
Structrl Battery

AFRL/RX
Irradiation

Scientific Challenges & Program Achievement

- Self-healable or in-situ remendable structural materials *(1st-ever program; world lead)*
- Microvascular composites for continuous self-healing and self-cooling systems *(1st-ever program; world lead)*
- Structural integration of energy harvest/storage capabilities *(1st-ever program on harvest capabilities; DoD lead)*
- Neurological system-inspired sensing/diagnosis/ actuation network *(pot'l world lead)*
- Biomolecules for sensing and actuation *(pot'l world lead)*
- Mechanized material systems and micro-devices for reconfigurable structures *(DoD lead)*
- Experimental nano-mechanics *(DoD lead)*

Transformational Opportunities

- **Self-healable or in-situ remendable structural materials** ***– Quantum improvement in survivability of aerospace structures***
- **Microvascular composites for continuous self-healing and self-cooling systems** ***– Quantum improvement in survivability of aerospace structures & thermal management***
- **Structural integration of energy harvest/storage capabilities** ***– Self-sustaining UAV and hybrid-powered aircraft***
- **Neurological system-inspired sensing/diagnosis/ actuation network** ***– Autonomic state awareness in aerospace***
- **Mechanized material systems and micro-devices for reconfigurable structures** ***– Morphing wing aircraft & Neutralization of penetration threats***

PORTFOLIO TRENDS

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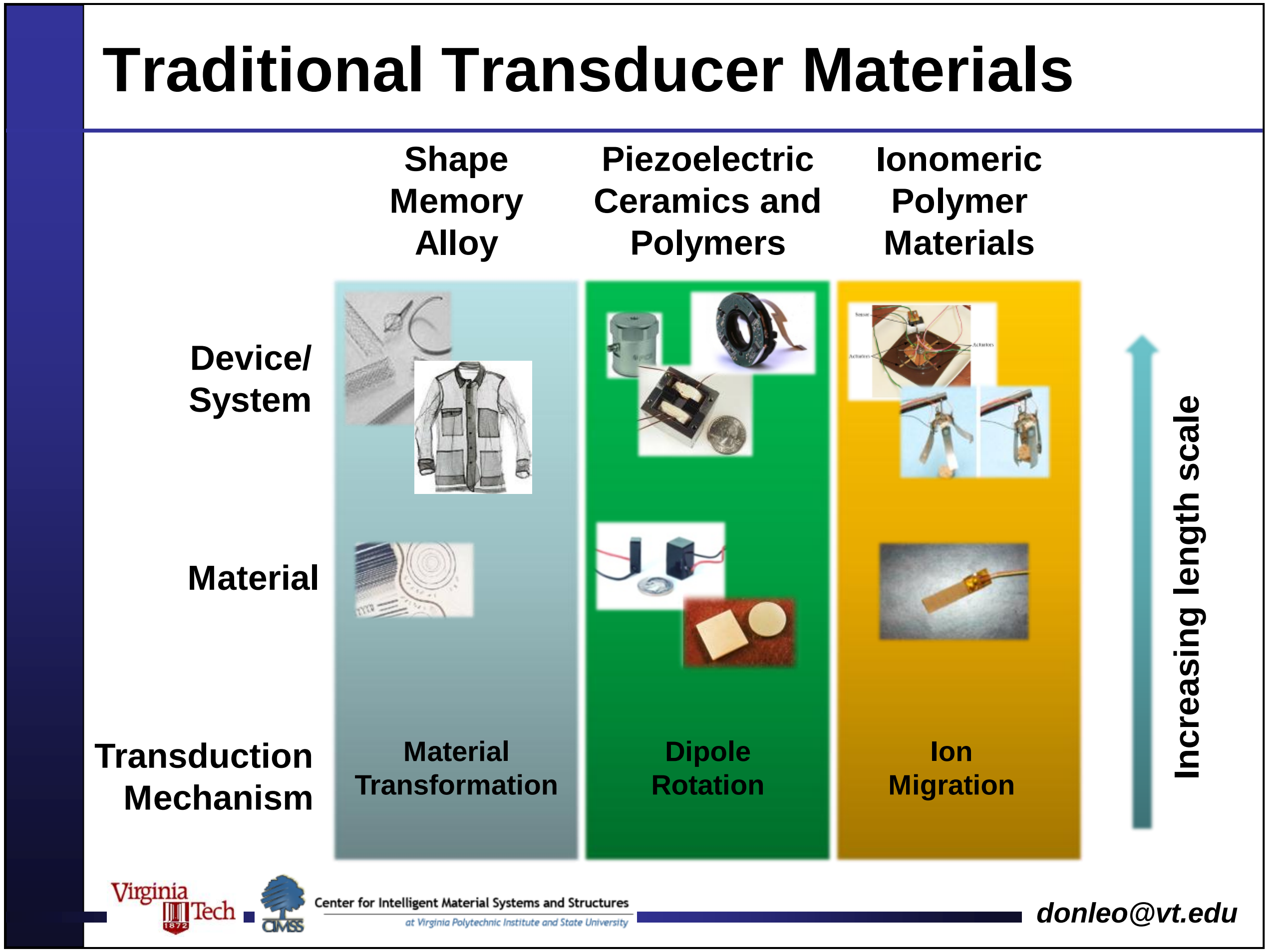
Actuation, Morphing & Threat Neutralization; ↗
Engineered Bio/Nano/Info-materials ↗

ENGINEERED DEVICES:
BEYOND CURRENT VISION

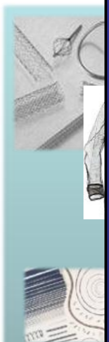


ENGINEERED DEVICES: *BEYOND CURRENT VISION*

Traditional Transducer Materials

Sh
Me
A

Device/ System



Material

Transduction Mechanism

Ma
Transf

Virginia Tech · CIMSS · Center for Intelligent
at Virg

The question we are studying …

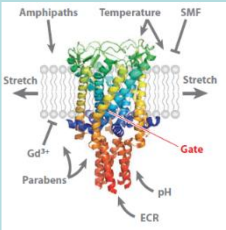
How can we use biomolecules to make completely new types of materials for engineered devices?

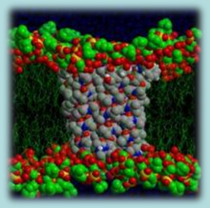
Device/ System	Sensors, Energy Capture and Conversion, Color Changes	Increasing length scale ↑
Material	Durable, Robust, Easy to Manufacture	
Transduction Mechanism	Channels, Pumps, Transporters	

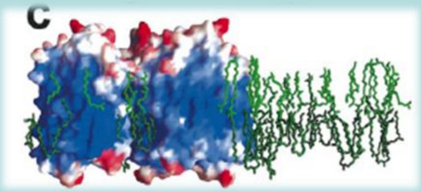
Virginia Tech · CIMSS · Center for Intelligent Material Systems and Structures at Virginia Polytechnic Institute and State University

donleo@vt.edu

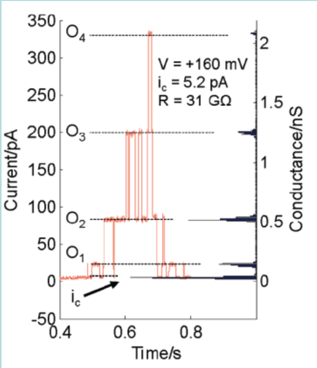
BRI'12 - BIOMOLECULES FOR SENSING *(VT/U TN/U MD/UIUC: Leo)*





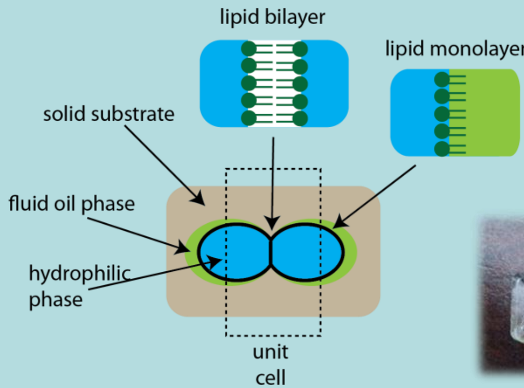


Structure of the **mechanically-activated** channel MscL (top left), the **voltage-gated** channel alamethicin (top right), and the **light-activated** channel bacteriorhodopsin (bottom).



Gating response of the voltage-gated channel alamethicin to an applied potential.

Over 3.5 billion years of evolution, nature has produced a highly diversified set of biomolecular transducers that exhibit a wide range of transduction properties.



A biomolecular unit cell utilizes the **stimuli-responsive** properties of biomolecules as a means of creating new transducer materials.

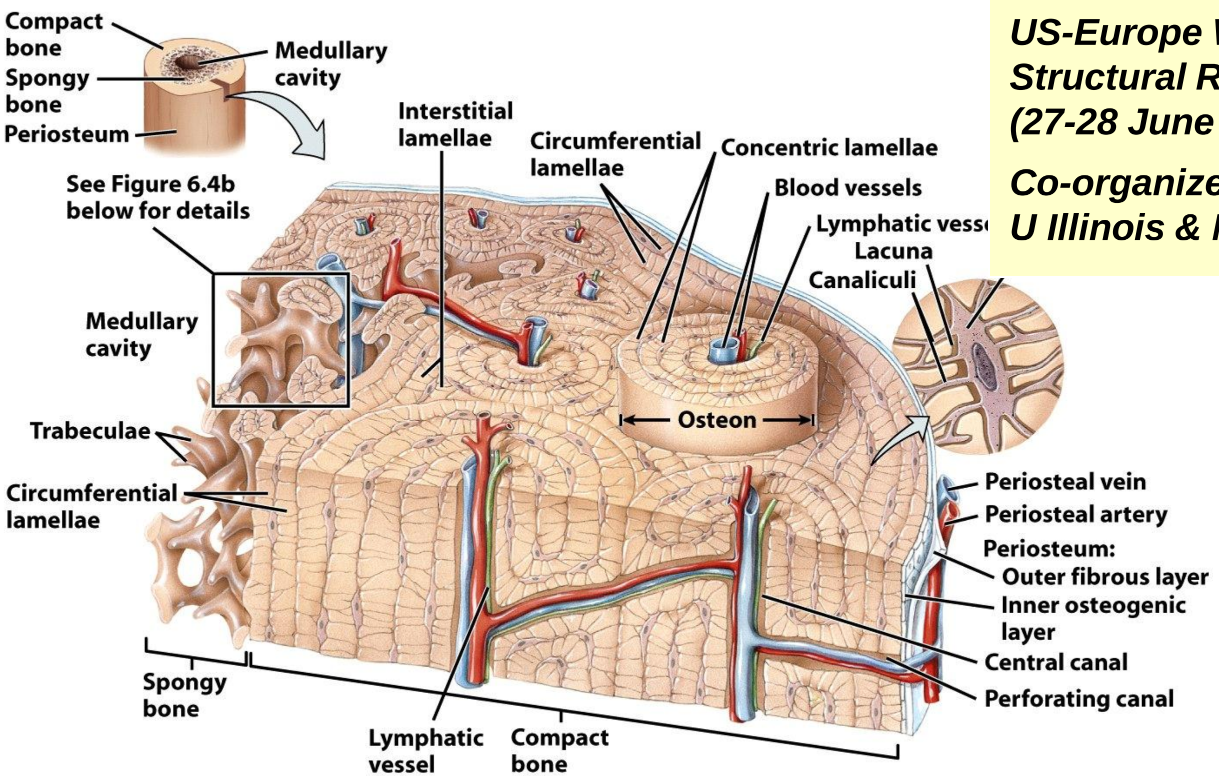
In the past two decades humans have been able controllably modify these transduction properties and incorporate them into durable material systems.

How can we utilize the stimuli-responsive properties of biomolecules to create a new class of transducer system?

Co-PM's: B. L. Lee, Hugh Delong

Design by Nature:
BONE REMODELING

Resorption vs Ossification; 4~20% renewal per year;
Subjecting a bone to stress will make it stronger



US-Europe Workshop on Structural Regeneration (27-28 June 2012, Venice)

Co-organized by AFOSR, ARO, U Illinois & Max Planck Inst.

Fig. 6-4a Anatomy and Physiology: From Science to Life © 2006 John Wiley & Sons

DCT'09: SUPER-CONFIGURABLE MULTIFUNCTIONAL STRUCTURES

Workshops:

(a) AFRL-wide Brainstorming Discussion (Arlington, VA, 26 February 2007)

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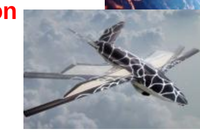
(e) AFRL-wide Round Table Discussion on DCT Topic (Eglin AFB, FL, 28 January 2008)

Objective

To establish new "**morphing**" aerospace structures capable of altering their **shape**, **functionality** and **mechanical properties** for **real-time optimization** in response to the changes in environments or operating conditions



Approach

- Develop new concepts for **structural reconfiguration**, **energy transduction mechanisms** and **system integration** allowing the combination of **UAV** and **space-deployable systems**.
- Indentify new **adaptive materials**, **mechanized material systems** and **micro-devices** for **sensing, communication** or **actuation**.
- Model the influences of **morphology**, **dimensionality** and **topography** on the **multifunctional performance** and **manufacturability**.

Capability/Payoff

- Reduce **weight/size** and increase the **system efficiency** by incorporating multi-functionality into load-bearing structures
- Allow **mission-specific** and **real-time optimization** of multi-functional performance of military systems
- Potential systems to be impacted are: **unmanned aerial vehicles (UAV)**, **sensor platforms**, **dash/loiter theatre dominance platforms**, **space deployable systems**, etc.

Programs Involved

Mechanics of Multifunctional Materials & Microsystems;
Structural Mechanics;
Polymer Composites;
High Temperature Materials 43

Transition from: Active Materials for Adaptive Structures

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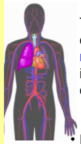

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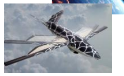

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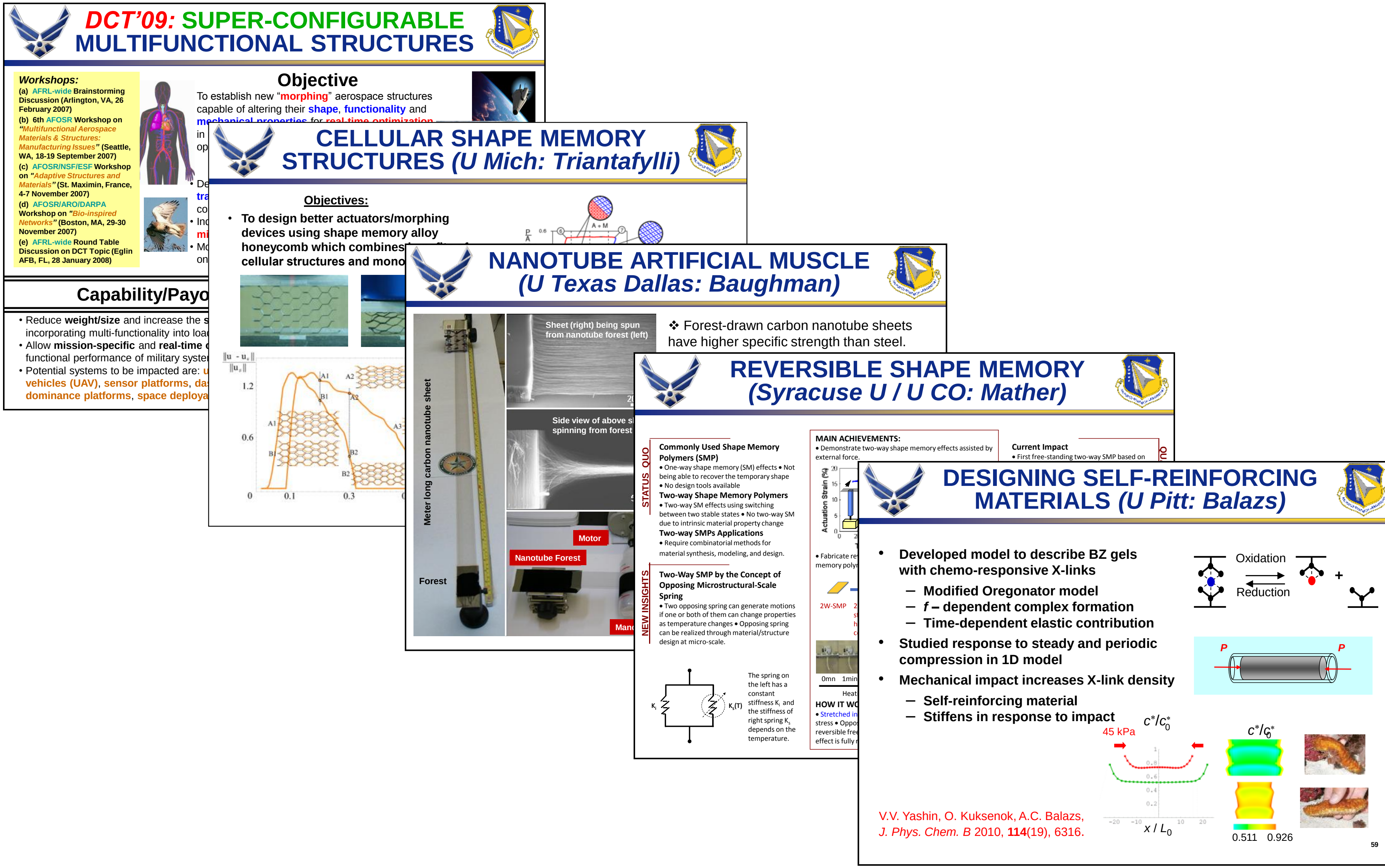

Transition to: Multifunctional Design of Morphing Air Vehicles

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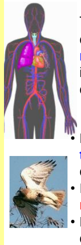

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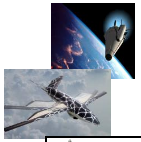

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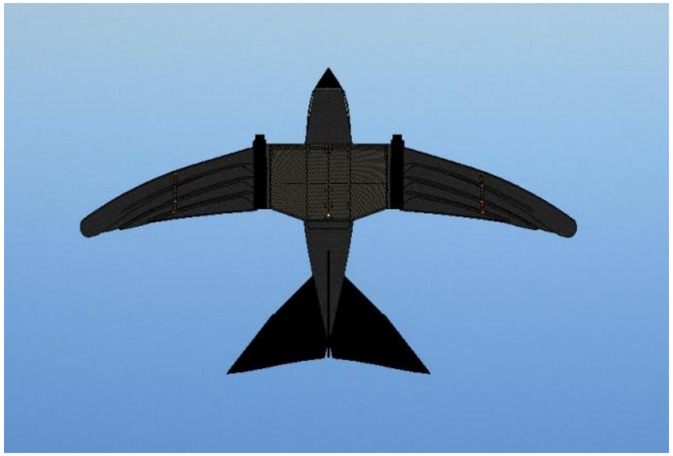
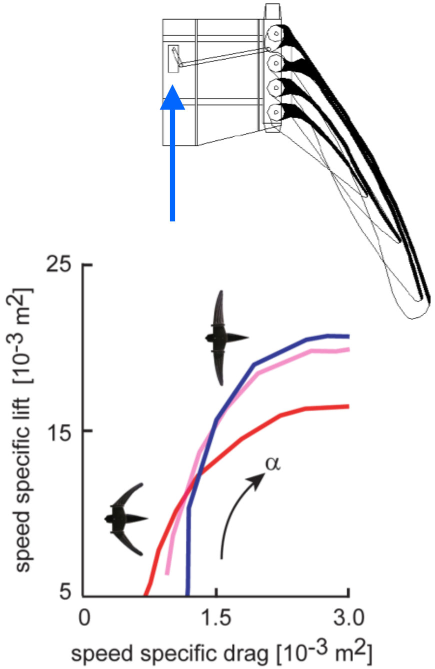
Programs In

Mechanics of Multif
Materials & Mic
Structural Mechanic
Polymer Composite
High Temperature M

BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)





1st Bird-like Morphing UAV (TU Delft-led team):

- Design of a **morphing wing** with **feathers** inspired by **birds**.
- A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- The 50cm long wing is built of **super-thin light-weight** carbon fiber **composites** with the plane weight of 100 gram.
- Successfully flew in an impressive wind force 5-6.

Transition to: Multifunctional Design of Morphing Air Vehicles

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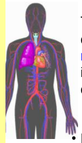

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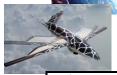

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Programs In…

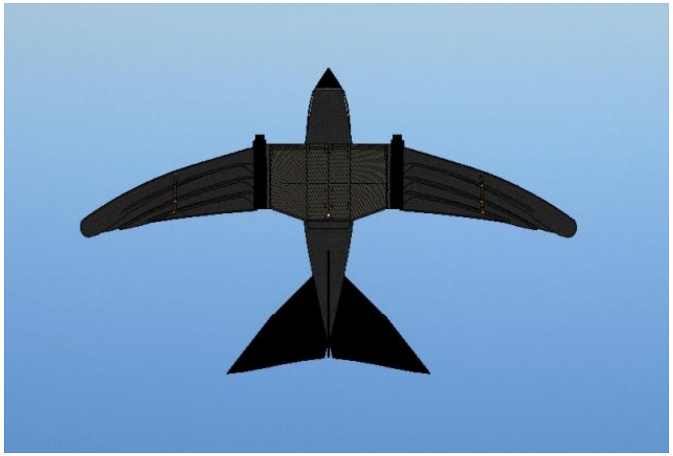
Mechanics of Multif…
Materials & Mic…
Structural Mechanic…
Polymer Composite…
High Temperature M…

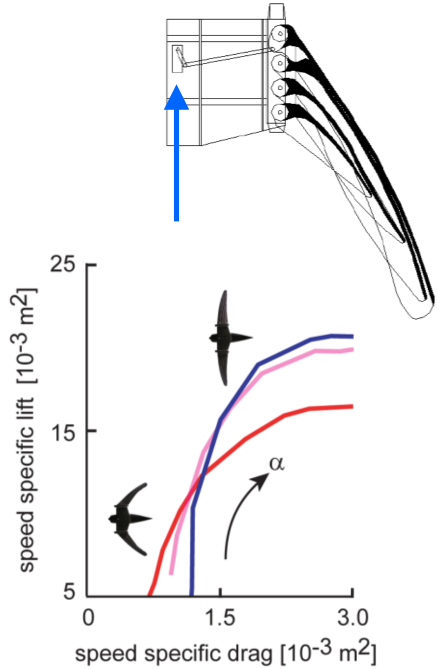
Objective:

To achieve **multifunctional design** of **morphing air vehicle** as an **autonomic** system (in collaboration with the expertise in *biomimetics*, *dynamics* and *control*)

BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)





1st Bird-like Morphing UAV (TU Delft-led team):

- Design of a **morphing wing** with **feathers** inspired by **birds**.
- A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- The 50cm long wing is built of **super-thin light-weight** carbon fiber **composites** with the plane weight of 100 gram.
- Successfully flew in an impressive wind force 5-6.

New Focus:

- ❖ Morphing air vehicles capable of altering the **geometry**, **surface area** and **mechanical properties** of wing structures
- ❖ Mimicking **"muscular-skeletal" system** of **bird wings**
- ❖ Deploying **mechanized active materials** and **computational metamaterials** for structural reconfiguration.

PROGRAM COLLABORATION

Emerging Frontiers in Research and Innovation (EFRI)

EFRI Topic Areas for FY 2009 / 2010

Two new research areas have been identified for the FY09 EFRI solicitation:

1. BioSensing & BioAc
2. Hydrocarbons from

The research commun
be considered for the
Frontiers in Research
following website http
topic idea along with
provided.

TOPIC 1 BIOSENSING

Shih C. Liu
Yogesh B. Gianchand
Leon Esterowitz
Rajinder Khosla
Eduardo Misawa
Lynn Preston

BioSensing and BioActuation
Proposed Research Opportunities/Challenges

1. ***Hierarchical Organization of Biological Systems***
   Uncover the unifying aspects underlying hierarchical bio-structures and bio-systems and use them for sensing and actuation; apply to new multi-scale and multi-functional sensor/actuator concepts.
2. ***Sensor Informatics Guided by Life***
   Create new knowledge that will be exploited in novel bio-inspired data mining and dynamic control, including capabilities to monitor, assess, and control living and engineered systems in sensor-rich environments.
3. ***Multifunctional Materials and Devices for Distributed Actuation and Sensing***
   Understand biological systems and mechanisms that lead to their ability to exhibit fault-tolerant actuation with a wide dynamic range, the production of practical means for producing artificial structures that exhibit similar behaviors, and their incorporation into useful engineered systems.
4. ***Forward Engineering & Design of Biological/Biomedical Components & Systems***
   Synthesize hybrid synthetic-living systems through systems-level integration of biological and engineered components that sense, actuate, compute, regenerate and efficiently allocate resources in order to achieve desired responses and functions.

Proposed for AFOSR-NSF Collaboration:

"Muscular-Skeletal System Inspired Reconfigurable Materials Design";

"Structural Regeneration & Remodeling"

Pot'l MURI or BRI

THE 2ND "MULTIFUNCTIONAL MATERIALS FOR DEFENSE" WORKSHOP

Theme: Sensing, Actuation & Energy Transduction

In conjunction with:

The 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on "Mechanics of Multifunctional Materials & Microsystems"

30 July-1 August 2012
Hilton Arlington Hotel, Arlington, VA

Workshop Co-Chairs:
Gregory Reich *(AFRL/RBSA)*
William Nothwang *(ARL/SEDD)*
James Thomas *(NRL)*

Organizing Committee:
B.-L. ("Les") Lee *(AFOSR), Co-Chair*
David Stepp *(ARO), Co-Chair*
Ignacio Perez de Leon *(ONR), Co-Chair*
William Baron *(AFRL/RBSA)*
Jeff Baur *(AFRL/RXBC)*
Mark Derriso *(AFRL/RBSI)*
Gregory Reich *(AFRL/RBSA)*
William Nothwang *(ARL/SEDD)*
Daniel O'Brien *(ARL/WMRD)*
James Thomas *(NRL)*

PORTFOLIO OVERVIEW

NAME: ***B. L. ("Les") Lee***

<u>BRIEF DESCRIPTION OF PORTFOLIO</u>:
Basic science for integration of emerging materials and micro-devices into future Air Force systems requiring multi-functional design

<u>LIST OF SUB-AREAS</u>:

- ***Design of Autonomic/Self-Sustaining Systems;***
- ***Design of Reconfigurable Systems;***

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Self-Diagnosis;
Self-Healing, Remediation & Structural Regeneration;
Self-Cooling & Thermal/Irradiation Management;
Energy Transduction & System Integration;
Actuation, Morphing & Threat Neutralization;
Engineered Bio/Nano/Info-materials

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Engineered Bio/Nano/Info-materials

***PI's** & Co-PI's:*

Tsu-Wei Chou (U Del)
Yuntian Zhu (NCSU)
Ioannis Chasiotis (UIUC)
Liping Liu (Rutgers U)^
David Kisailus (UC Riverside)*
Pablo Zavattieri (Purdue U)
Don Leo (VA Tech)#
S. Andrew Sarles (U TN)
Sergei Sukharev (U MD)
Narayan Aluru (UIUC)

^ YIP; * HBCU/MI; # BRI

PORTFOLIO OVERVIEW

NAME: *B.*

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- *Design*
- *Design*

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Self-Coolir

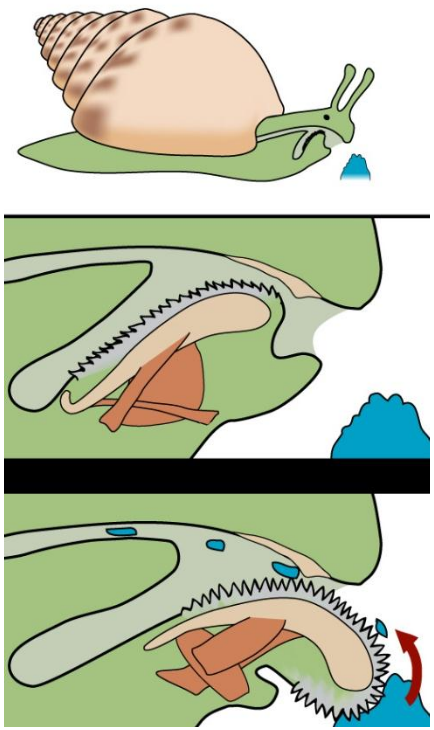
Energy Tra

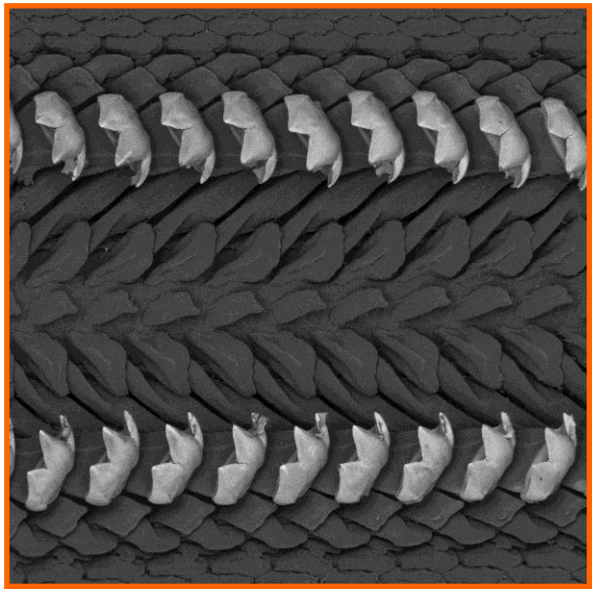
Actuation,

Subject:	***PI's** & Co-PI's:*
Thin Flexible CNT Composites	***Tsu-Wei Chou (U Del)*** *Yuntian Zhu (NCSU)*
>> Compliant Nano-spring Interfaces	***Ioannis Chasiotis (UIUC)***
Designing Structures for Functional Materials	***Liping Liu (Rutgers U)^***
Damage-tolerant Biological Composites	***David Kisailus (UC Riverside)**** *Pablo Zavattieri (Purdue U)*
>> Biomolecular Materials for Sensing & Actuation	***Don Leo (VA Tech)#*** *S. Andrew Sarles (U TN)* *Sergei Sukharev (U MD)* *Narayan Aluru (UIUC)*
>> New	***^ YIP; * HBCU/MI; # BRI***

Engineered Bio/Nano/Info-materials

DAMAGE TOLERANT BIOLOGICAL COMPOSITES *(UCR: Kisailus)*



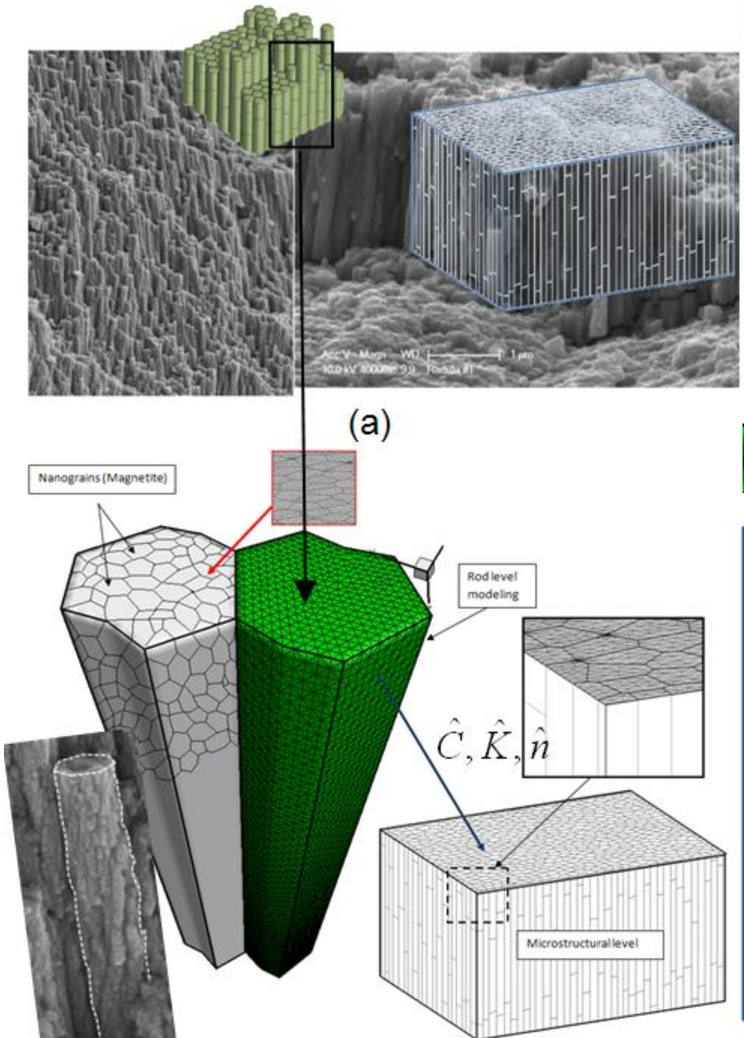


Radular Teeth of Chiton (elongated mollusk)**:**

- Ribbon-like structure covered with small dentacles for tearing food into pieces
- Composed of an nanocrystalline iron phosphate core with a magnetite veneer edge
- The deposited mineral phase is ultra hard and abrasion resistant and 4-fold modulus difference at core-veneer interface effectively deflects crack propagation

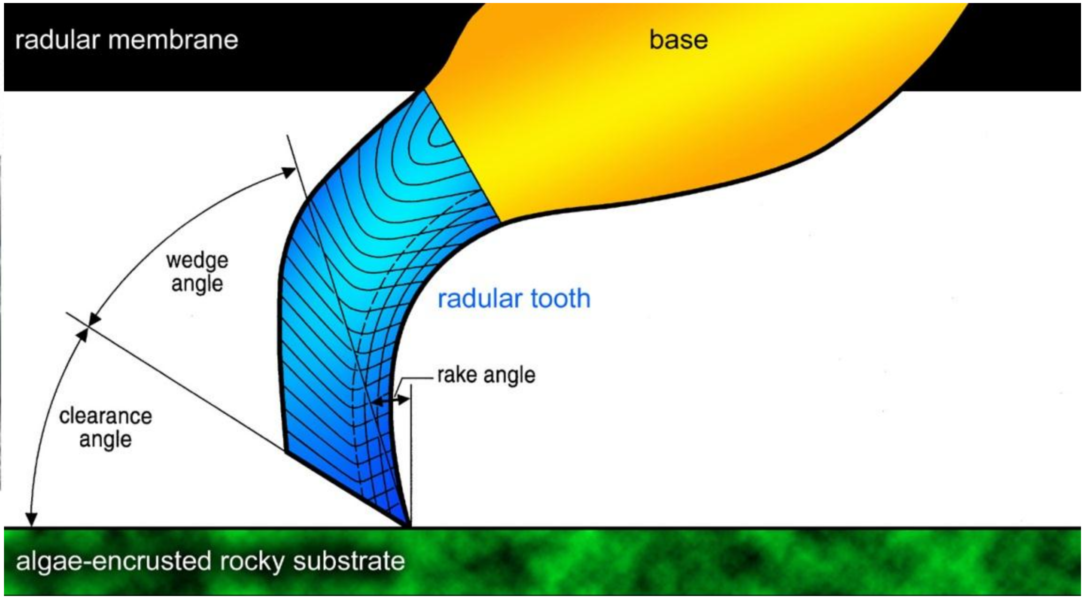
DAMAGE TOLERANT BIOLOGICAL COMPOSITES *(Purdue U: Zavattieri)*

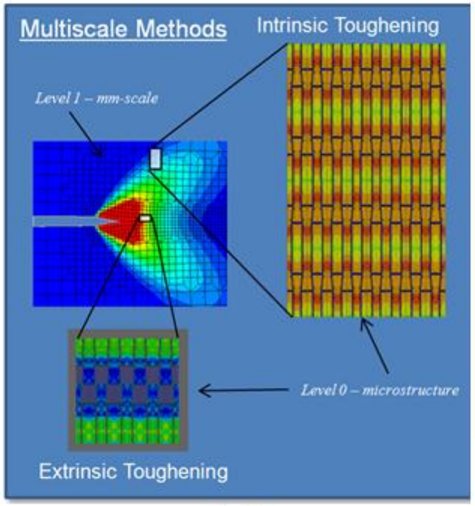
Relevance: Bio-inspired design of **gears** or **abrasion-resistant materials**



(a)

(b)



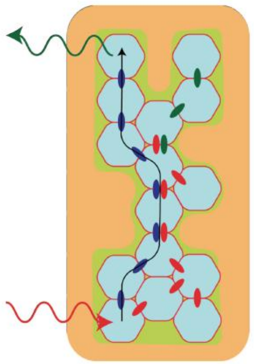


(c)

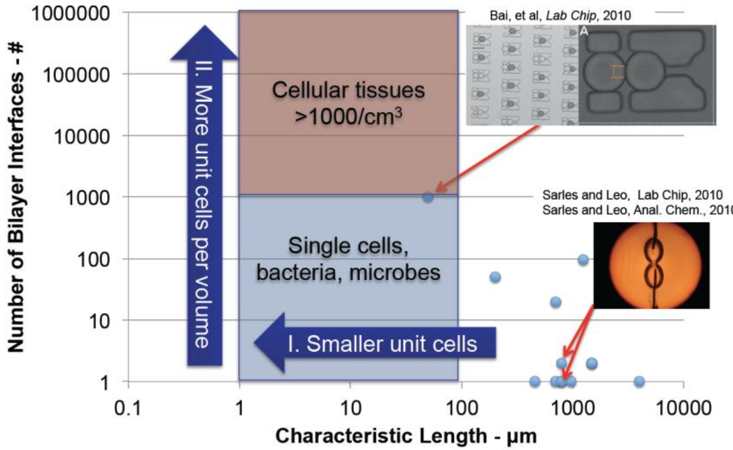
(a) Micromechanical model of rod like structure of radular tooth, including a potential RVE. (b) Hierarchical model to connect nano- to microscale. (c) Hierarchical model to connect the microscale to macroscopic fracture tests.

BRI'12 - BIOMOLECULES FOR SENSING *(VT/U TN/U MD/UIUC: Leo)*

GOALS



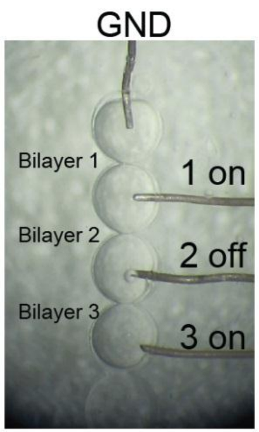
Biomolecular Network

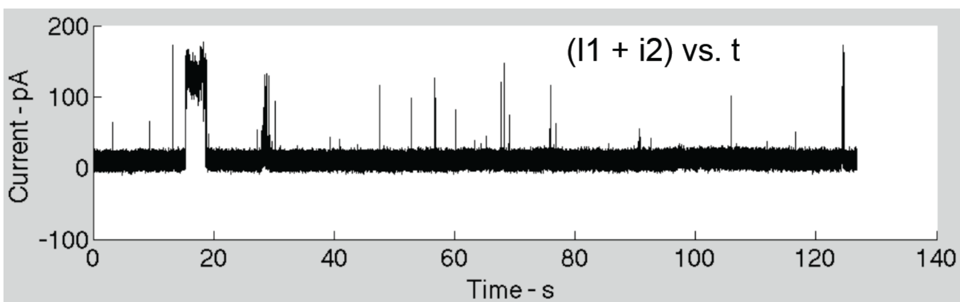


Synthesis and Fabrication of Multi-Cellular Arrays:

- Autonomic, multifunctional behavior can only be achieved by incorporating large numbers of stimuli-responsive "cells" into the material.
- The program will establish in-depth understanding of the methods required for synthesizing and fabricating multicellular material systems with characteristic length scales less than 100 microns and functional densities that approach those of natural systems.

ACCOMPLISHMENTS

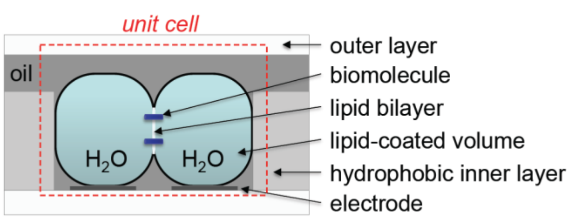




Fabricated **a four-cell material system** with a characteristic length scale on the order of 100s of microns.

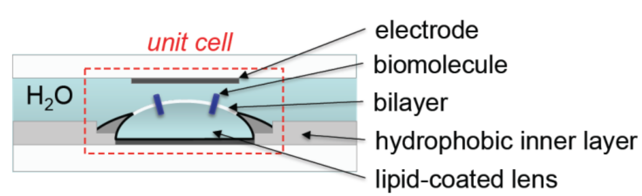
Measured **voltage-gated channel activity** across **multiple interfaces** in this four-cell material.

NEXT STEPS



Inject and arrange using microfluidics

Print and dewet



Begin the development of **injection** and **printing** methodologies for multi-cell arrays.

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H. Jerry Qi (U CO)
Martin Dunn (U CO)
Shiv Joshi (NextGen)
Sharon Swartz (Brown U)
Nakhiah Goulbourne (VA Tech)
Minoru Taya (U WA)
Frank Ko (U Brit Columbia)
Nicolaus Correll (U CO)
Ray Baughman (U Texas Dallas)
A. John Hart (U Mich)^
Aaron Dollar (Yale U)^
Xin Zhang (Boston U)
C. T. Sun (Purdue U)
Olivier Mondain-Monval (CNRS)
Thomas Siegmund (Purdue U)
Anna Balazs (U Pitt)
Nicole Zacharia (Texas A&M)
Richard Vaia (AFRL/RXBN)
Greg Reich (AFRL/RBSA)

^ YIP

PORTFOLIO OVERVIEW

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- *Design*
- **Design**

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Actuation,

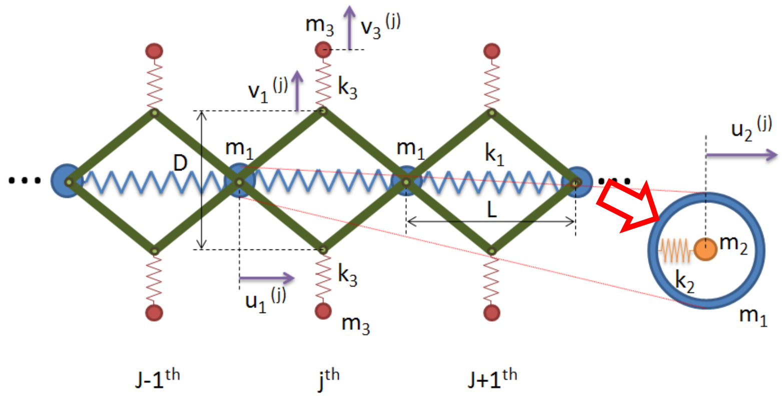
Engineere

Subject:	***PI's** & Co-PI's:*
<< Reversible Shape Memory Polymer Composites	***Patrick Mather (Syracuse U)*** *H. Jerry Qi (U CO)* *Martin Dunn (U CO)*
<< Ultra-Maneuverable Bat Technologies	***Shiv Joshi (NextGen)*** *Sharon Swartz (Brown U)* *Nakhiah Goulbourne (VA Tech)*
<< Bio-inspired Reconfigurable Structures	***Minoru Taya (U WA)*** *Frank Ko (U Brit Columbia)*
Self-Assembly and Self-Repair of Structures	***Nicolaus Correll (U CO)***
Artificial Muscles for Large Stroke & High Force	***Ray Baughman (U Texas Dallas)***
Morphing CNT Microstructures	***A. John Hart (U Mich)^***
Active Cells for Multifunctional Structures	***Aaron Dollar (Yale U)^***
Metamaterial Enhanced MEMS	***Xin Zhang (Boston U)***
Acoustic Metamaterials w Local Resonance	***C. T. Sun (Purdue U)***
Ultrasonic Tunable Ultra-Damping Metamaterials	***Olivier Mondain-Monval (CNRS)***
Macroscale Meta-Materials	***Thomas Siegmund (Purdue U)***
Active Materials w Sensory & Adaptive Capabilities	***Anna Balazs (U Pitt)***
Mechano-Responsive Polymer Systems	***Nicole Zacharia (Texas A&M)***
>> Mechanically-Adaptive Materials	***Richard Vaia (AFRL/RXBN)***
Thermally-Activated Reconfigurable Systems	***Greg Reich (AFRL/RBSA)***

>> New**; **<< Concluded

^ YIP

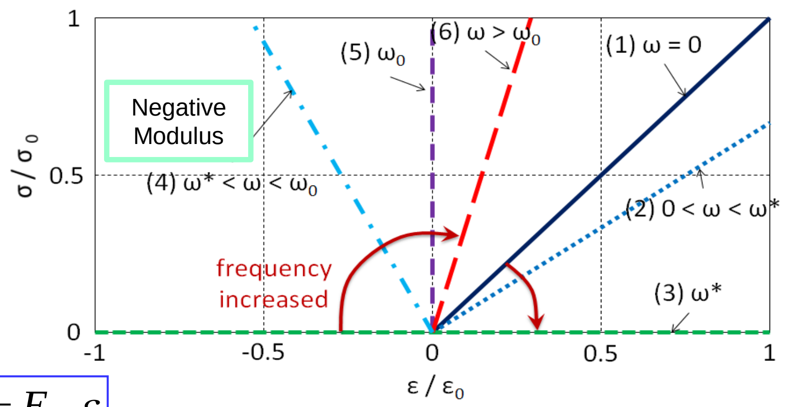
METAMATERIALS WITH NEGATIVE MODULUS *(Purdue U: Sun)*



- A model is formulated for **acoustic metamaterials** with **locally resonant** microstructures.
- Under sinusoidal loading the **stress-strain relation** depends on the **frequency**.
- Near the local resonance frequency ω_0 of the side masses, the effective modulus is extremely large.
- The **effective Young's modulus** becomes **negative** in a certain frequency range.
- **Wave amplitude decays** when its frequency falls inside this **band gap**, especially if the frequency is near the frequency ω^* .
- At the lower bound frequency of the band gap ω^*, the effective modulus approaches zero.

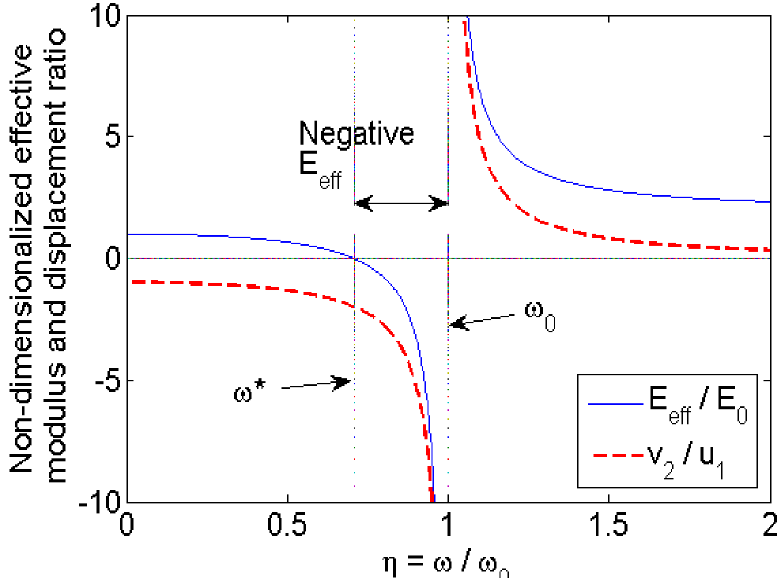
Effective stress-strain relations

ω_0: local resonance frequency



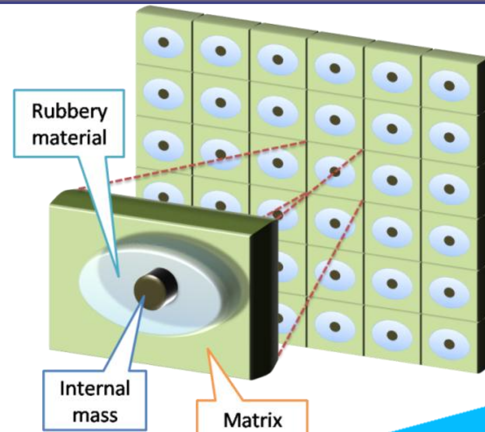
$$\sigma = E_{eff}\,\varepsilon$$

Effective Young's modulus

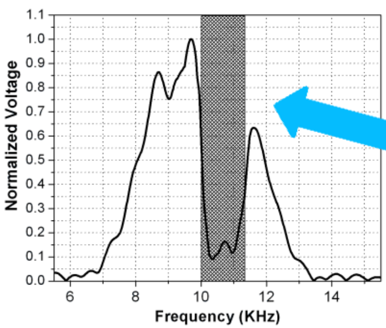


METAMATERIALS WITH NEGATIVE MODULUS *(Purdue U: Sun)*

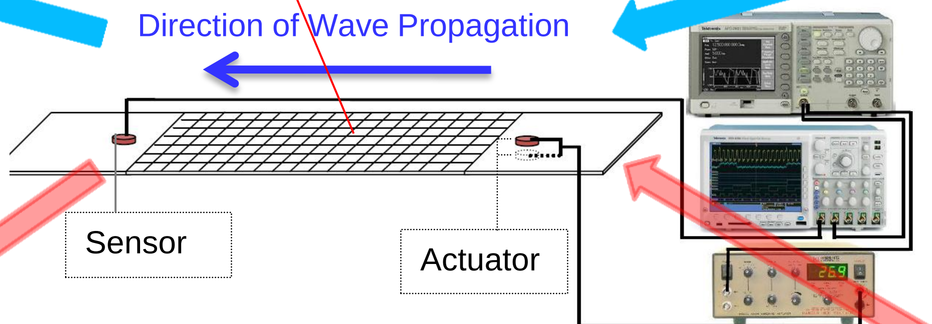
Goals
- Develop acoustic metamaterials for mitigating dynamic/impulsive loads
- Utilize the unusual wave propagation behavior of acoustic metamaterials in signal transmission, vibration isolation, and wave mode switching.

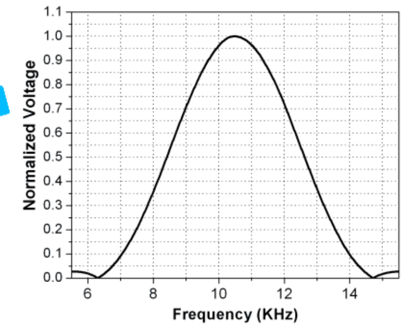


Acoustic Metamaterial

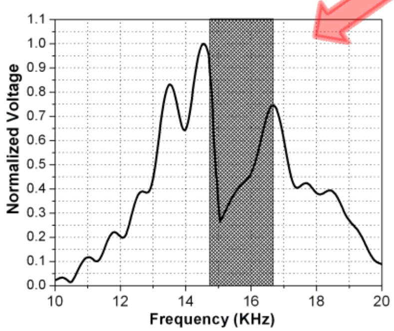


Output of In-plane Pulse





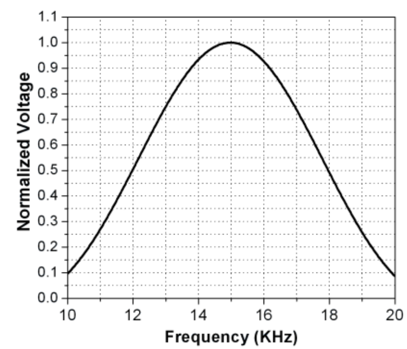
Input of In-plane Pulse



Output of Out-of-plane Pulse

Experimental Setup
- Piezoelectric actuator patches were used for generating in-plane and out-of-plane waves
- Piezoelectric sensor patch was used for wave reception.

Result
- Significant **attenuation of wave amplitude** after passing through the metamaterial.
- **Band gap regions** of experimental results agree with that of the theoretical prediction (shaded regions).



Input of Out-of-plane Pulse

BAT-INSPIRED MORPHING WING
(NextGen/Brown U/VPI: Joshi)

CURRENT STATE

- Reconfigurable hovering ultra-maneuerable **bat** technologies (RHUMBAT) offers potential benefits in operational robustness.
- Most research has focused on recreating three **degrees of freedom** (DOF's) assoc with this motion: **flap**, **lag**, and **feather**
- Small vehicle size and low inertia make **fine-scale control** required for envisioned missions difficult.

NEW INSIGHTS

- New unique approach considers **actuators** that are **distributed across the structure**.
- Provides detailed analysis for selection of **actuation DOF** using motion capture and revealing **complex morphologies of joints**.
- **Wing membrane characterization** shows **thickness inhomogeneities** to be considered in materials selection.

Data Smoothing, Motion Trajectory

- Motion capture data improved
- Motion trajectory defined for humerus and radius

Right wing assembly

Skeletal Assembly

- Bones assembled in CAD
- CAD model guides mechanical design

Robotic Wing

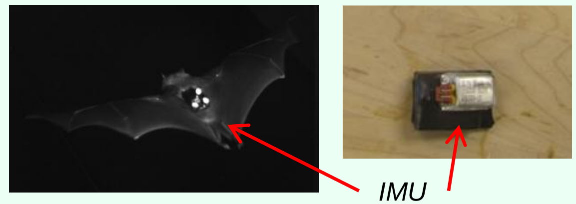
- 4 DOF
- High flapping frequency

Preliminary design

MAIN ACHIEVEMENTS (Cont'd):

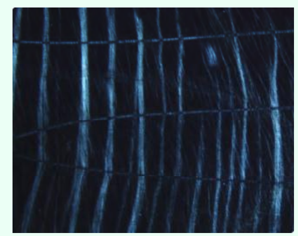
Inertial Measurement (IM)

- Acceleration and angular velocities recorded for straight and obstructed flights
- Dorsal mount miniature wireless IM Unit (IMU)



Biological Experiments

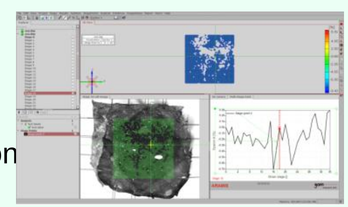
- Examined wing fiber under polarized light
- Guides constitutive model development



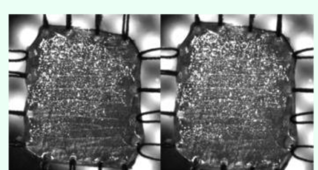
Wing fibers

Mechanical Characterization of Bat Membrane

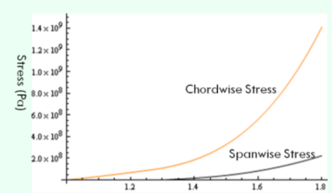
- Strain experiments
- Constitutive modeling
  - -Fiber bundle dist.
  - -Fiber bundle comp.
  - -Base matrix corrugation
- Result satisfy material anisotropy property



Strain analysis



Biaxial loading

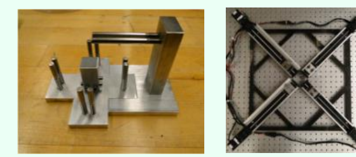


Simulated Stress-Strain Curve

QUANTITATIVE IMPACT

Current Impact

- In depth understanding of **bat skeletal structure** and **skeletal dynamics** during flight
- **Materials analysis** for **structural** & **aerodynamic surfaces**
- Translation of **bat dynamics** to **robotic system**



Improved suturing and biaxial setup

END-OF-PHASE GOAL

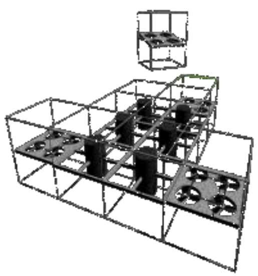
- **High-fidelity models** for components and integrated structure representative of a bat-wing
- Quantitative evaluation of **flight performance**, **energy consumption** / **efficiency**
- Estimates of **weight**, **volume** and **geometry** of a **robotic bat-wing**
- **Guidelines** to develop an autonomous, hovering, highly maneuverable, **bat-like MAV**

SELF-ASSEMBLY & SELF-REPAIR
(U CO: Correll)

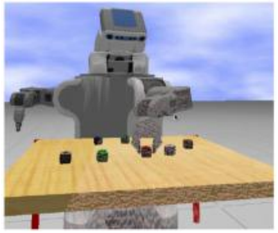
Objectives:

- Reconfiguration planning for smart structures with **embedded sensing**, **computation** and **actuation**
- Take into account ***physical constraints*** including gravity, wind and vibration
- **Enabling materials** with the ability to **self-reconfigure** and **self-repair**

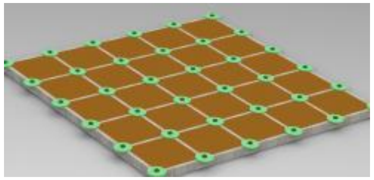
Smart Structures



Flying/self-mobility



External actuation



In-material sensing, computation and actuation

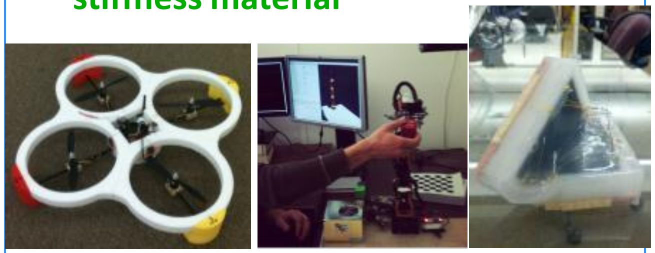
Approach:

- Combination of finite element analysis and real-time physics **simulation** with discrete search to find suitable reconfiguration paths.
- Embedding of intelligence for sensing and control of **internal/external actuators**

Achievements:

Platform development

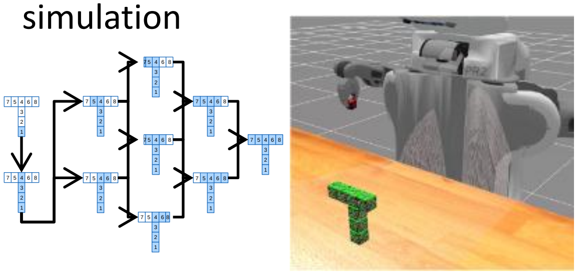
- Begun development of light-weight **in-air self-assembly test-bed**
- Begun development of **manipulation test-bed**
- Begun development of **variable stiffness material**



Light-weight in-air module; robotic assembly; variable stiffness material with embedded sensing/actuation

Reconfiguration planning

- Initial focus: **robotic assembly** under gravity constraints
- Discrete/Continuous **search framework** combining graph-based search, FEA and full-physics simulation



Assembly graph of a T-structure (left), **full-physics simulation** (right)

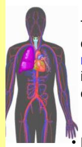
Perspectives:

- **Novel structural components** that can change their shape, function and appearance
- **Reconfigurable materials** to change function taking into account and in response to physical constraints

Transition to: Multifunctional Design of Morphing Air Vehicles

DCT'09: SUPER-CONFIGURABLE MULTIFUNCTIONAL STRUCTURES

Workshops:
(a) AFRL-wide Brainstorming Discussion (Arlington, VA, 26 February 2007)
(b) 6th AFOSR Workshop on "*Multifunctional Aerospace Materials & Structures: Manufacturing Issues*" (Seattle, WA, 18-19 September 2007)
(c) AFOSR/NSF/ESF Workshop on "*Adaptive Structures and Materials*" (St. Maximin, France, 4-7 November 2007)
(d) AFOSR/ARO/DARPA Workshop on "*Bio-inspired Networks*" (Boston, MA, 29-30 November 2007)
(e) AFRL-wide Round Table Discussion on DCT Topic (Eglin AFB, FL, 28 January 2008)



Objective
To establish new "morphing" aerospace structures capable of altering their shape, functionality and mechanical properties for real-time optimization in response to the changes in environments or operating conditions

Approach
- Develop new concepts for structural reconfiguration, en[...] transduction mechanisms and system integration allow[...] combination of UAV and space-deployable systems.
- Indentify new adaptive materials, mechanized material s[...] micro-devices for sensing, communication or actuation[...]
- Model the influences of morphology, dimensionality and[...] on the multifunctional performance and manufacturabil[...]

Capability/Payoff
- Reduce **weight/size** and increase the **system efficiency** by incorporating multi-functionality into load-bearing structures
- Allow **mission-specific** and **real-time optimization** of multi-functional performance of military systems
- Potential systems to be impacted are: unmanned aerial vehicles (UAV), sensor platforms, dash/loiter theatre dominance platforms, space deployable systems, etc.

Programs In[...]
Mechanics of Multif[...]
Materials & Mic[...]
Structural Mechani[...]
Polymer Composite[...]
High Temperature M[...]

Objective:

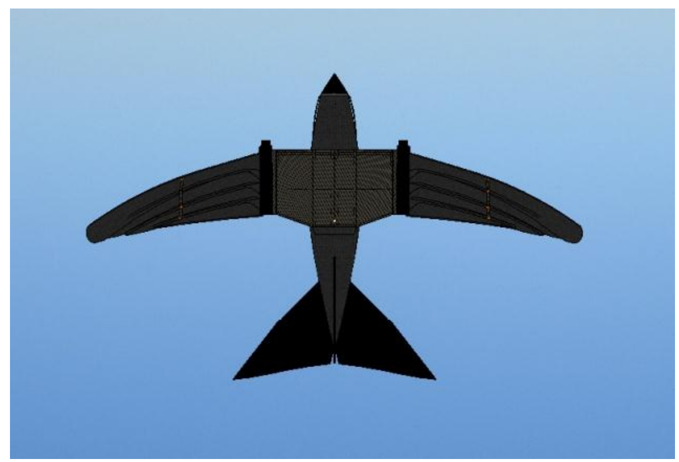
To achieve **multifunctional design** of **morphing air vehicle** as an **autonomic** system (in collaboration with the expertise in *biomimetics*, *dynamics* and *control*)

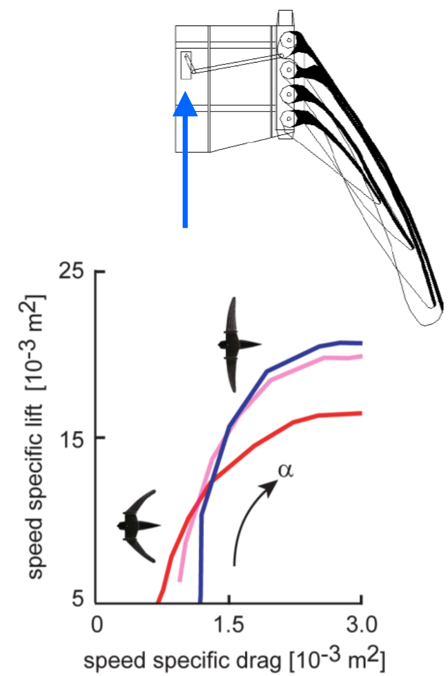
New Focus:

- ❖ Morphing air vehicles capable of altering the **geometry**, **surface area** and **mechanical properties** of wing structures
- ❖ Mimicking **"muscular-skeletal" system** of **bird wings**
- ❖ Deploying **mechanized active materials** and **computational metamaterials** for structural reconfiguration.

BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)





1st Bird-like Morphing UAV (TU Delft-led team):
- ➢ Design of a **morphing wing** with **feathers** inspired by **birds**.
- ➢ A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- ➢ The 50cm long wing is built of **super-thin light-weight** carbon fiber **composites** with the plane weight of 100 gram.
- ➢ Successfully flew in an impressive wind force 5-6.

PORTFOLIO OVERVIEW

NAME: *B. L. ("Les") Lee*

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- *Design of Reconfigurable Systems;*

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Self-Healing, Remediation & Structural Regener
Self-Cooling & Thermal/Irradiation Management
Energy Transduction & System Integration;
Actuation, Morphing & Threat Neutralization;
Engineered Bio/Nano/Info-materials

***PI's** & Co-PI's:*

Sven Bilén (Penn St U)
Michael Strano (MIT)
***Max Shtein (U Mich)** #*
Henry Sodano (U FL)
Dan Inman (VA Tech)
Greg Carman (UCLA)
Wonbong Choi (FL Int'l U)
Ioannis Chasiotis (UIUC)
Hugh Bruck (U MD)
Gleb Yushin (GA Tech)^
Carmel Majidi (Carnegie-Mellon)^
Michael Durstock (AFRL/RXBN)
Benji Maruyama (AFRL/RXBN)
John Coggin (Prime Photonics)+
Shashank Priya (VA Tech)+

^ YIP**; **# PECASE**; **+ STTR

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Subject:	***PI's** & Co-PI's:*
<< ***Energy Harvesting via Electrodynamic Tethers***	***Sven Bilén (Penn St U)***
Environmental Hydrocarbon Harvesting via CNT	***Michael Strano (MIT)***
Energy Harvesting Textile Composites	***Max Shtein (U Mich)*** #
Active Structural Fibers for Multif'l Composites	***Henry Sodano (U FL)***
Vibration Suppression and Energy Harvesting	***Dan Inman (VA Tech)***
Nanoscale Based Thermal Energy Harvesting	***Greg Carman (UCLA)***
Flexible Battery of Graphene-CNT Hybrid	***Wonbong Choi (FL Int'l U)***
Integrity of Energy Harvest/Storage Materials	***Ioannis Chasiotis (UIUC)***
Integrated Solar Cells for MAV Wings	***Hugh Bruck (U MD)***
>> << ***Electrodes for Multifunctional Li-ion Battery***	***Gleb Yushin (GA Tech)***^
>> ***Energy Harvesting for Soft-Matter Machines***	***Carmel Majidi (Carnegie-Mellon)***^
Nanomaterials for Structural Batteries	***Michael Durstock (AFRL/RXBN)*** *Benji Maruyama (AFRL/RXBN)*
Hybrid Energy Harvesting Systems	***John Coggin (Prime Photonics)***+ *Shashank Priya (VA Tech)*+
>> New; ***<< Concluded***	***^ YIP***; ***# PECASE***; ***+ STTR***

Energy Transduction & System Integration;

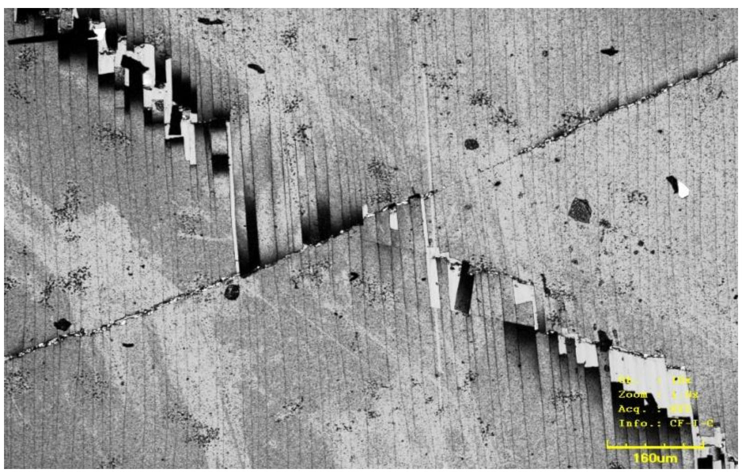
Actuation, Morphing & Threat Neutralization;

Engineered Bio/Nano/Info-materials

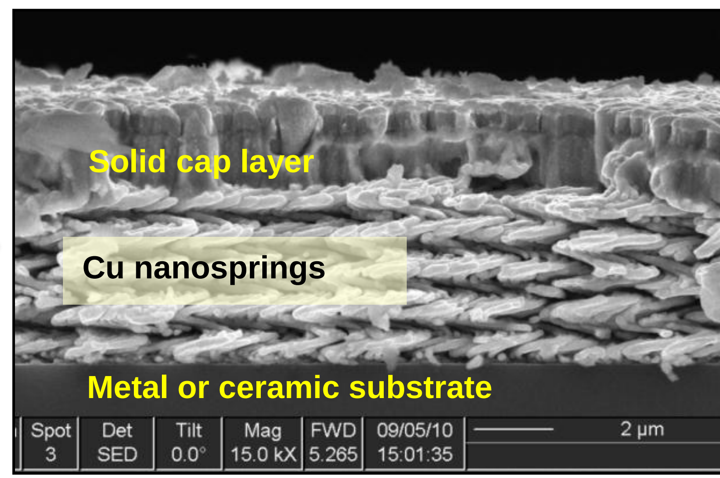
STRUCTURAL INTEGRITY OF ENERGY DEVICES *(UIUC: Chasiotis)*

***Challenges* for Integration of Solar Cells & Batteries into Load-Bearing Composite Structures**:

- Materials degradation of thin film solar cells and batteries during curing of the composite materials.
- **Thermal mismatch** between thin films and the underlying structure generate high strains. As a result, the integrated structure could suffer **wavy blister** type **delamination** and **fragmentation failure**.
- Prior efforts to integrate thin film solar cells with CFRPs pointed out **0.3%** and **1% critical strains** for **performance reduction** and **fragmentation failure** respectively.
- **Micron-** or **nano-scale springs** of metallic or ceramic thin films benefit from size effects to provide **compliant**, yet strong and tough, **multifunctional interface** *(A new grant initiated)* .
- High capacity battery electrodes are prone to **cracking** under stress upon lithiation.

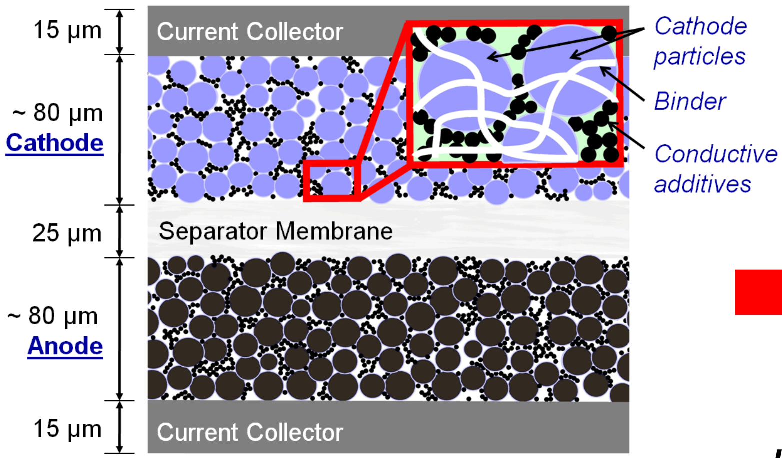


Fragmentation of a 2-µm thick ZnO/Si solar cell bonded on $(\pm 45°)_4$ laminate loaded according to the arrows. The vertically parallel strips are ZnO/Si film fragments.

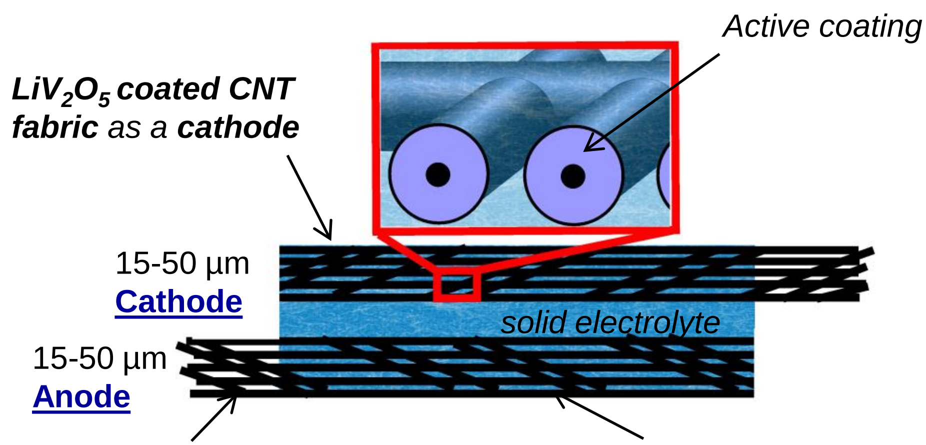


Film of nanosprings fabricated by glancing angle deposition (GLAD).

YIP'09 - LOAD BEARING BATTERIES (GA Tech: Yushin)



Cu current collector; ***Graphite anode*** *with PVDF binder;* ***$LiMO_x$ cathode*** *(M: Co, Mn, Ni)*



Uncoated portion of CNT fabric *serves as a* ***current collector***

Strong and flexible ***Mg-*** *or* ***Si- coated CNT fabric*** *as an* ***anode****; Cannot be replaced with uncoated CNT due to mechanical degradation induced by Li*

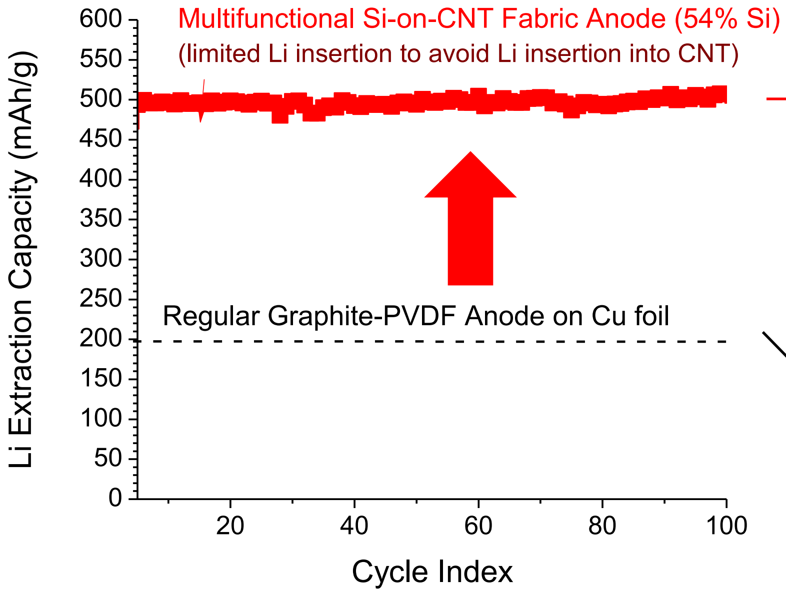
Traditional Electrodes & Cell Architecture

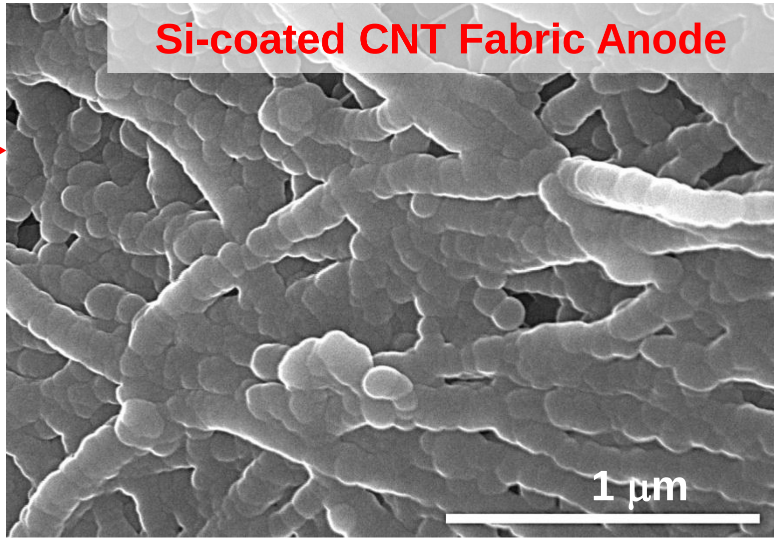
- Low electrical conductivity
- Low thermal conductivity
- Heavy/bulky metal foils
- No mechanical strength

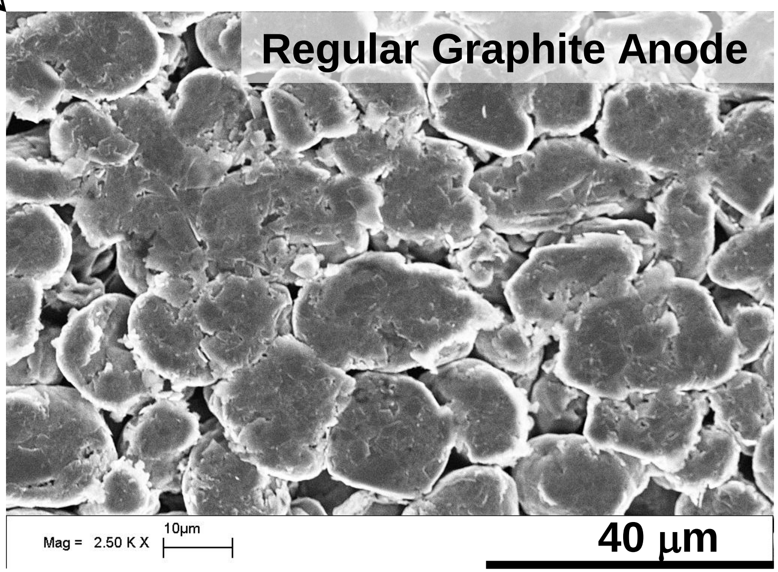
Multifunctional Nanocomposite Fabric for Electrodes & Current Collector

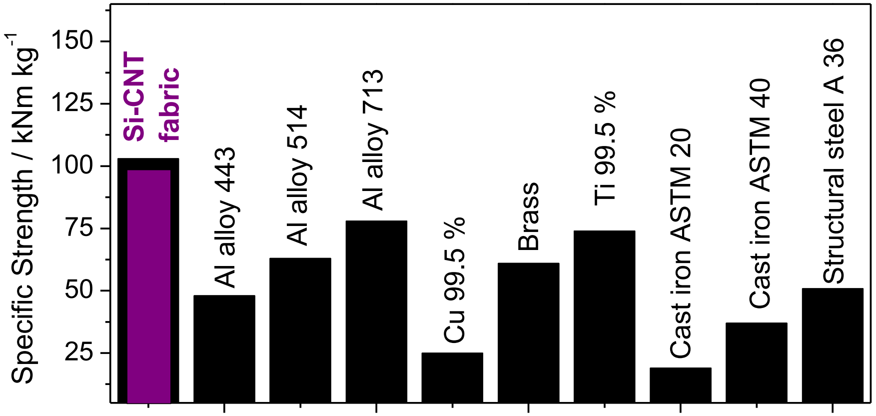
- Ultra-high electrical conductivity
- High thermal conductivity
- No metal foil current collectors needed
- High mechanical strength
- Enhanced safety *(with solid electrolyte)*

YIP'09 - LOAD BEARING BATTERIES (GA Tech: Yushin)









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Alma Hodzic (U Sheffield)
Tom Darlington (Nanocomposix)+
Tony Starr (SensorMetrix)+
Tom Hahn (UCLA)+
Nancy Sottos (UIUC)
Scott White (UIUC)
Jeffrey Moore (UIUC)

Jimmy Xu (Brown U)
Ajit Roy (AFRL/RXBT)
Abraham Stroock (Cornell U)
Noel Holbrook (Harvard U)
Patrick Kwon (Mich St U)
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Mary Frecker(Penn St U)
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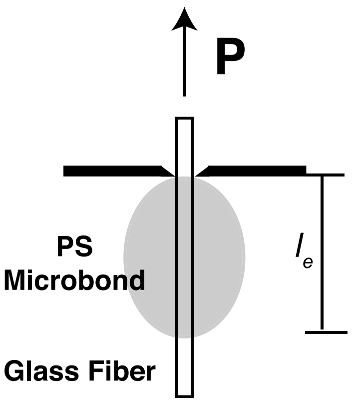
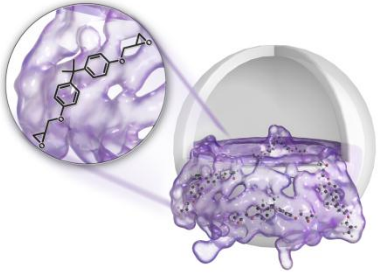
Subject:	***PI's &*** *Co-PI's:*
<< Inkjet-Assisted Creation of Self-Healing Layers	***Alma Hodzic (U Sheffield)***
<< Remendable Composites w Resistive Heating	***Tom Darlington (Nanocomposix)+***
	Tony Starr (SensorMetrix)+
	Tom Hahn (UCLA)+
<< Interfacial Self-Healing in Composites	***Nancy Sottos (UIUC)***
Regeneration & Remodeling of Composites	***Scott White (UIUC)***
	Jeffrey Moore (UIUC)
<< Thermal Signature Reduction & EMI Shielding	***Jimmy Xu (Brown U)***
<< Carbon Fiber Morphology for Thermal Materials	***Ajit Roy (AFRL/RXBT)***
Plant-mimetic Heat Pipes	***Abraham Stroock (Cornell U)***
	Noel Holbrook (Harvard U)
New Generation of Perspirable Skin	***Patrick Kwon (Mich St U)***
Variable Thermal Conductivity Structures	***George Lesieutre (Penn St U)***
	Mary Frecker(Penn St U)
	James Adair(Penn St U)
Graphene Composites for Lightning Protection	***Assimina Pelegri (Rutgers U)***
Microvascular Systems for Mass/Energy Transport	***Aaron Esser-Kahn (UC Irvine)^***
>> Multifunctional Poro-Vascular Composites	***Jim Thomas (NRL)***
>> Composites under High Energy Irradiation	***Jeff Baur (AFRL/RXBC)***
	Ajit Roy (AFRL/RXBT)
>> New; << Concluded	*^ YIP; + STTR*

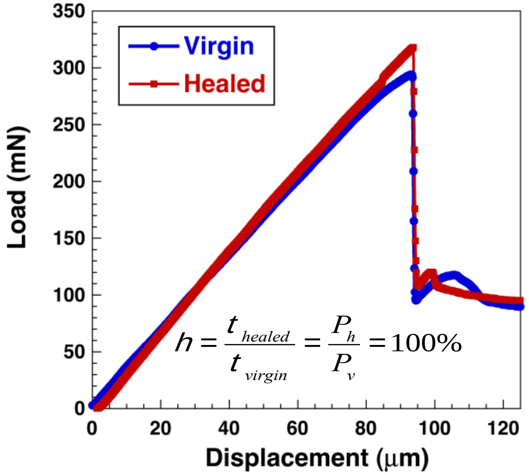
INTERFACIAL SELF-HEALING IN COMPOSITES *(UIUC: Sottos)*

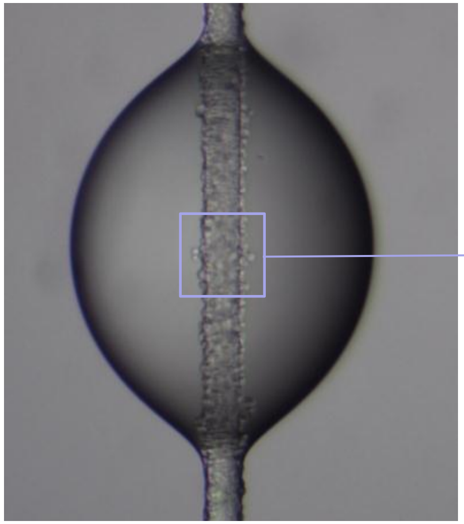
Single fiber microbond test



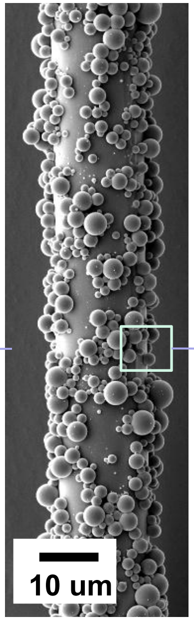
EPA solvent + EPON 862 resin healing chemistry



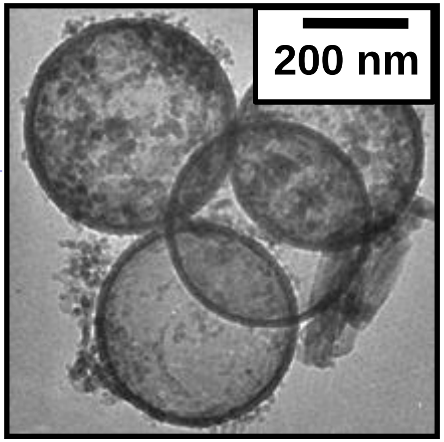


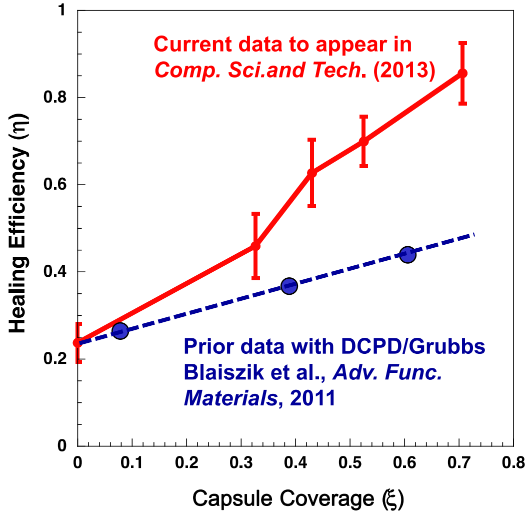


Functionalized glass fiber



TEM image of nanocapsules

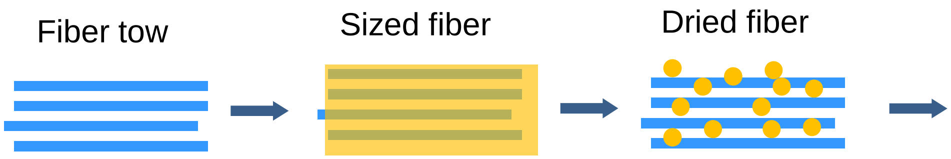


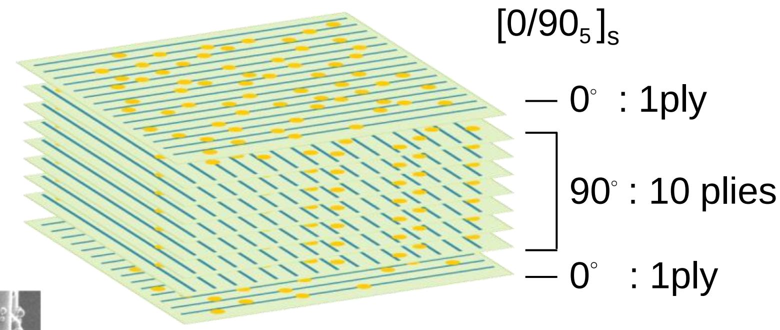


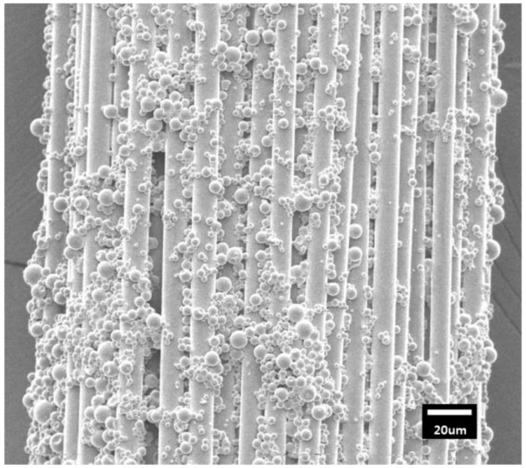
- **Full recovery of interfacial adhesion is observed for glass fibers with the capsules of EPA solvent + EPON 862 resin outperforming DCPD/Grubbs system.**

INTERFACIAL SELF-HEALING IN COMPOSITES *(UIUC: Sottos)*

- **Successfully processed the 1st self-healing prepreg in continuous production mode**







SEM image of E-glass fiber tow (200 count) with 3.3 μm diameter PU/UF microcapsules

E-glass fiber/epoxy resin
Matrix: EPON862/EPIKURE3274
Microcapsules
Core: 97:3 EPA(solvent)/EPON862
Shell: Polyurethane/polyUF shell

Proposed:

STTR (incl. Phase III) program covering multidisciplinary research on "self-healing composites" and involving the academia, AFRL and industry

- **Cross-ply laminates of self-healing composite with well dispersed microcapsules were fabricated from prepreg.**

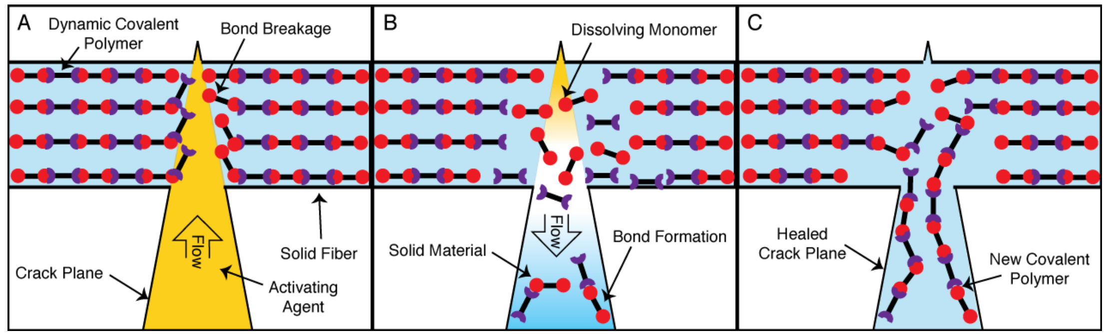
STRUCTURAL REMODELING
(UIUC: White/Moore) - Update

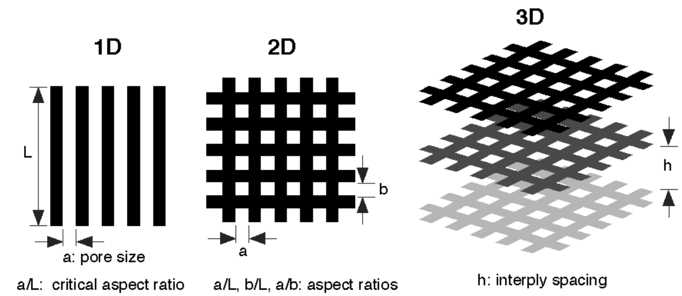
Regeneration in Nature:

Tree skink lizard

Linckia starfish

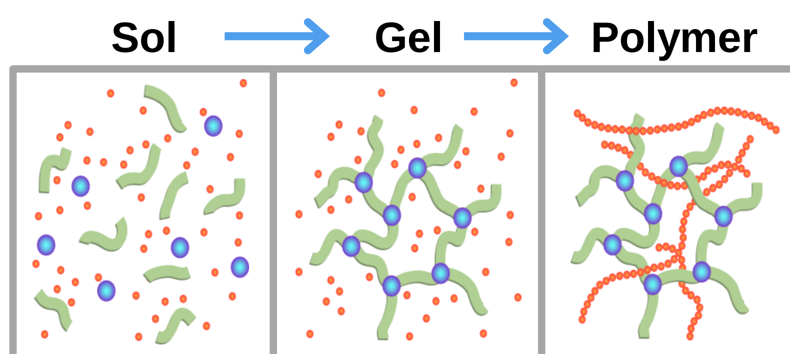
Approach: Dynamic Polymers + Inert Scaffolds





Accomplishments:

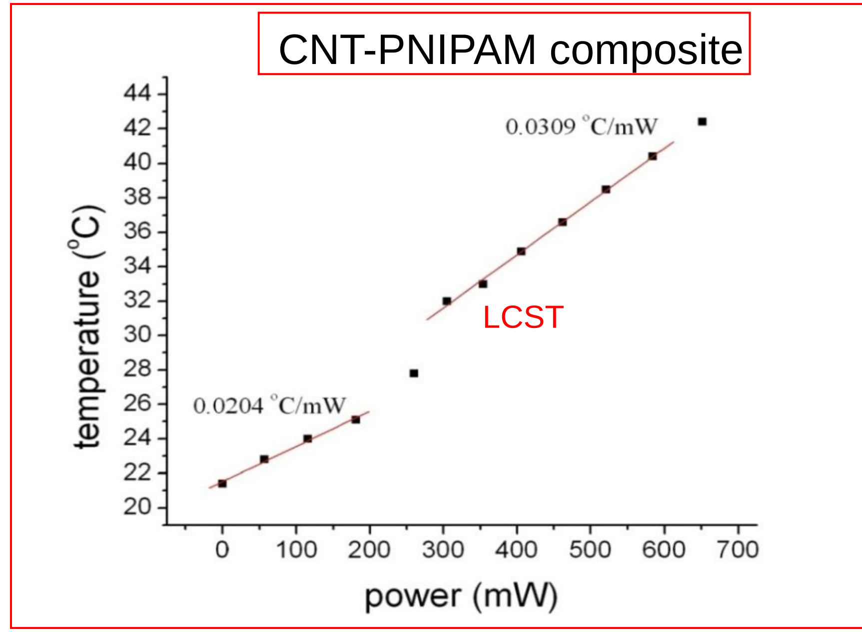
- Synthesis of dynamic polymers which undergo stimuli-responsive (de)polymerization via **reversible covalent bonds** (i.e. liquid to solid and vice versa).
- Systematic study of structure-property relationships for dynamic polymers based on **ionic bonds** that are generally stronger and widely used in biological systems such as sacrificial bonds and proteins.
- A new class of material called **ionic molecular glass** which form a rigid network of ionic bonds below Tg .
- Developed novel **bi-stage chemistry** for regeneration allowing independent temporal control of **sol-gel** and **gel-polymer** transitions

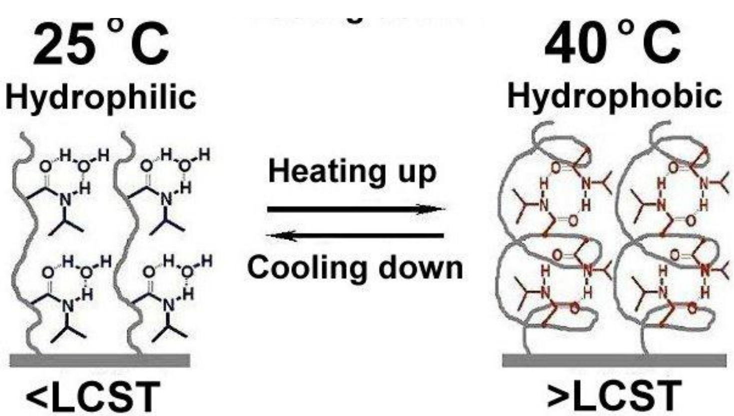


SELF-COOLING COMPOSITES
(Brown U: Xu)

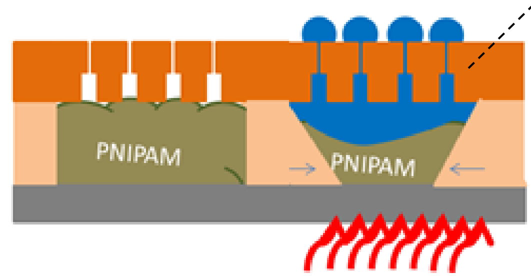
Phase Changing Polymer - Poly(N-isopropylacrylamide) (PNIPAM)

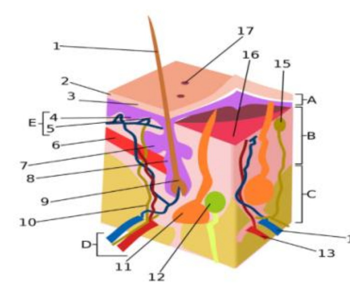
- When heated in water above Lower Critical Solution Temperature (LCST) of ~32°C, it undergoes a reversible phase transition from a swollen hydrated state to a shrunken dehydrated state, losing ~90% of volume.
- Melting point depends on molecular weight: 96°C for molecular weight of 20,000.
- Signature of polymer phase-change is still seen at ~32°C with high heating rate for CNT reinforced composites with PNIPAM matrices.





Proposed: **Synthetic skin for self-regulated cooling ('sweating') leading to thermal signature reduction**





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Michael Bevan (Johns Hopkins U)
Alexander Bogdanovich (NCSU)
Philip Bradford (NCSU)
fu-Kuo Chang (Stanford U)
Akira Todoroki (Tokyo Tech)
fu-Kuo Chang (Stanford U)*
*Xian Wang (Stanford U)**
*Boris Murmann (Stanford U)**
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^ YIP; * MURI; + STTR

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***Subject**:*	***PI's &** Co-PI's:*
<< Nanocomposites for Sensing & Actuation	***Erik Thostenson (U Del)^***
EM Tunable Fluids & Reconfigurable Antennas	***Gregory Huff (Texas A&M)***
	Zoubeida Ounaies (Penn St U)
	Michael Bevan (Johns Hopkins U)
Shear Pressed CNT Sheets for Strain Sensing	***Alexander Bogdanovich (NCSU)***
	Philip Bradford (NCSU)
>> Self-Diagnostic Adhesive for Bonded Joints	***fu-Kuo Chang (Stanford U)***
Damage Detection w Time Domain Reflectometry	***Akira Todoroki (Tokyo Tech)***
Bio-inspired Intelligent Sensing Materials	***fu-Kuo Chang (Stanford U)****
	*Xian Wang (Stanford U)**
	*Boris Murmann (Stanford U)**
	*Robert McLeod (U CO)**
	*Greg Carman (UCLA)**
	*Yong Chen (UCLA)**
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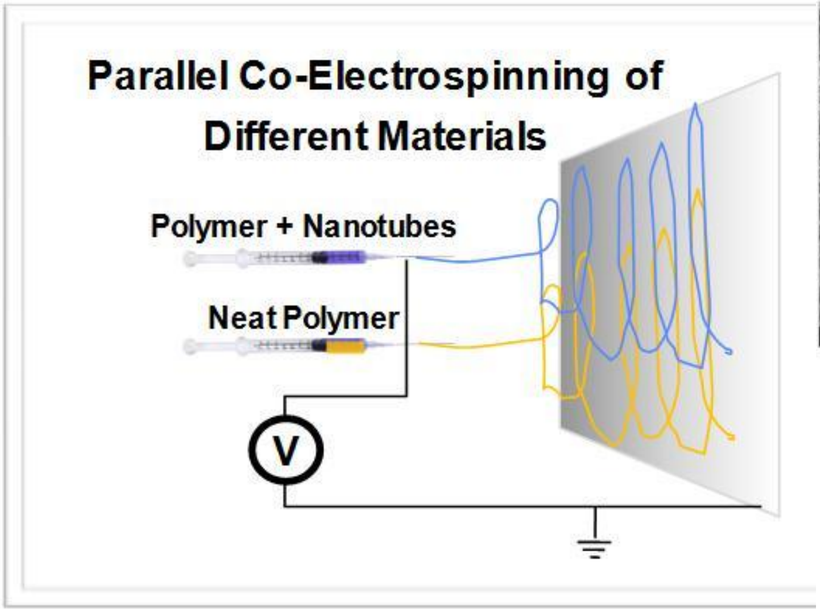
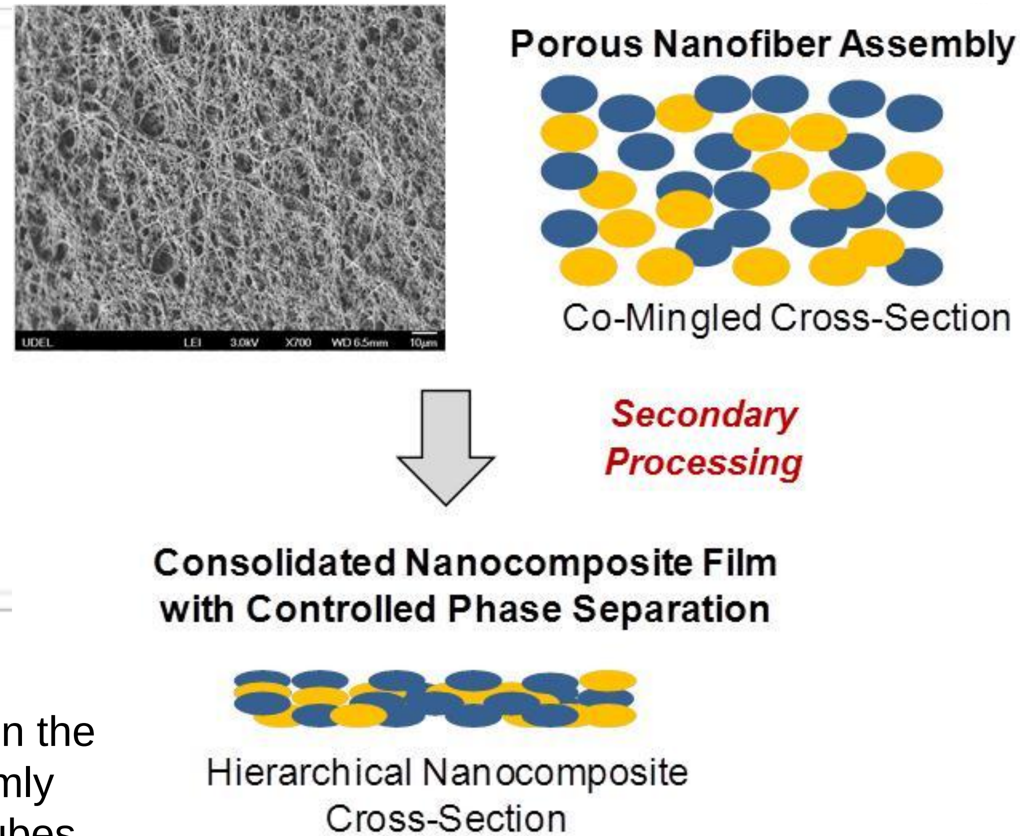
	*Rahmat Shoureshi (NYIT)**
	*Frank Ko (U Brit Columbia)**
Embedded Sensors & Actuators for MAV	***Ben Dickinson (AFRL/RWGN)***
>> Load-Bearing Antennas of Conductive Textiles	***Yakup Bayram (PaneraTech)+***
	John Volakis (Ohio St U)+
>> New; << Concluded	***^ YIP; * MURI; + STTR***

YIP'09 - NANOCOMPOSITES FOR SENSING *(U Del: Thostenson)*





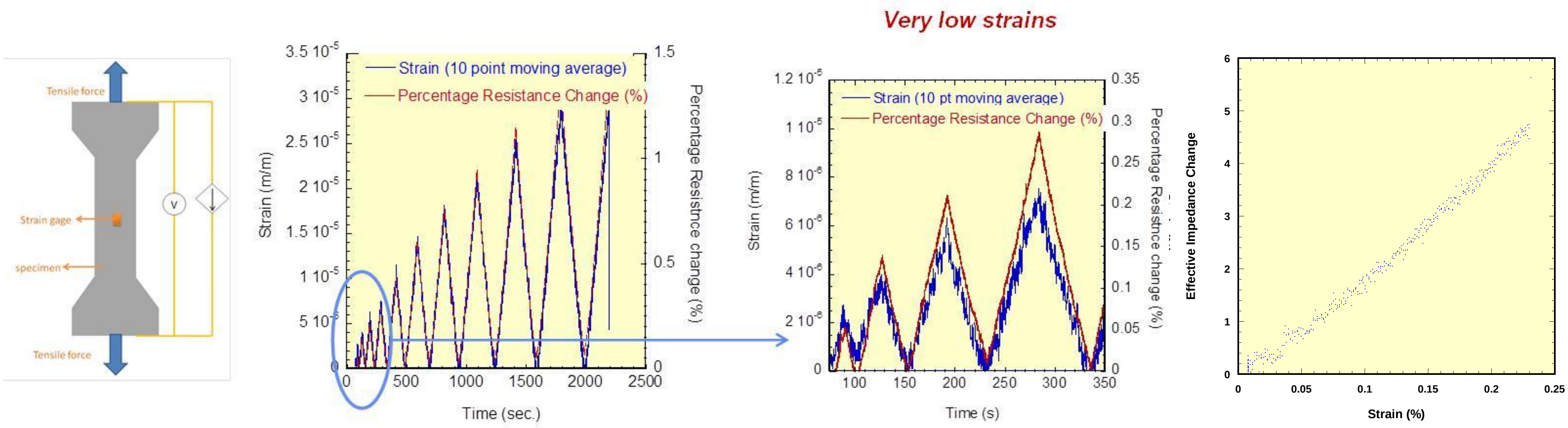
Co-mingled Nanofibrous Films

- Entanglement of the electrospun jets in the instability region can result in a uniformly co-mingled film of fibers where nanotubes are confined within individual filaments.
- Secondary-processing of co-mingled micro/nanofiber assemblies in a dense film results in a self-reinforced hierarchical composite with active polymer matrix.

Breakthrough in Composites Processing

- Rapid consolidation of thermoplastics
- Greater control over morphology of nano-reinforcement at high concentration

YIP'09 - NANOCOMPOSITES FOR SENSING *(U Del: Thostenson)*



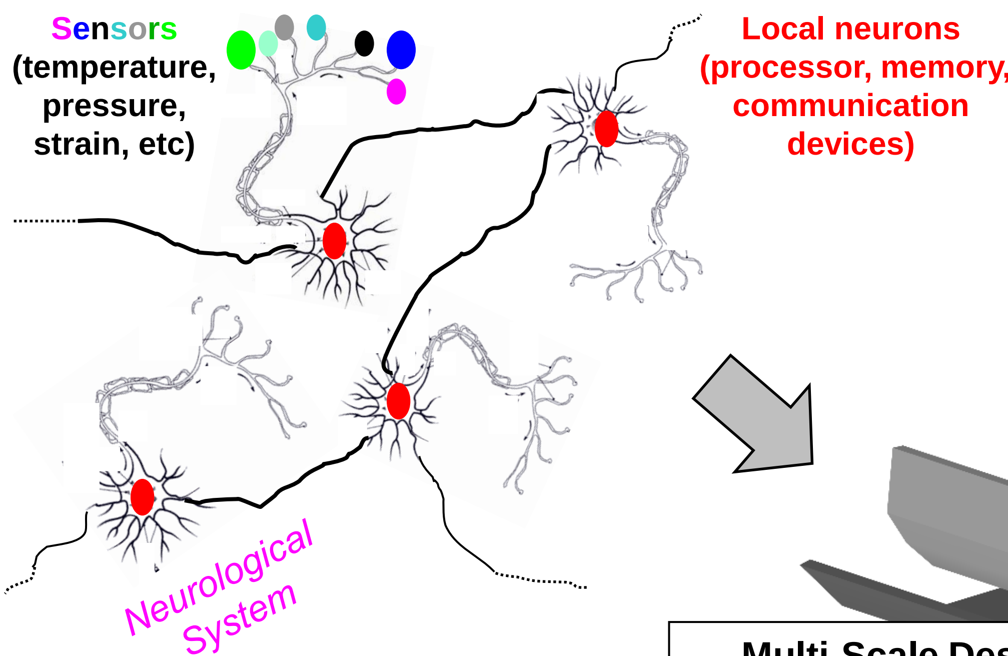
CNT (0.001) - PVDF

Accomplishments:

- The **electromechanical** response of **piezoelectric nanocomposites** is established at **high frequencies** utilizing a time-domain reflectometry approach.
- The integration of small quantities of carbon nanotubes impart apparent dielectrorestrictive response and capability for **non-contact strain sensing**.
- High-frequency **effective impedance changes** are directly related to changes in **dielectric** properties associated with **strain**
- Alteration of the **percolating network** can result in significant changes to the **resistance-strain behavior** in films and foams of nanocomposites.

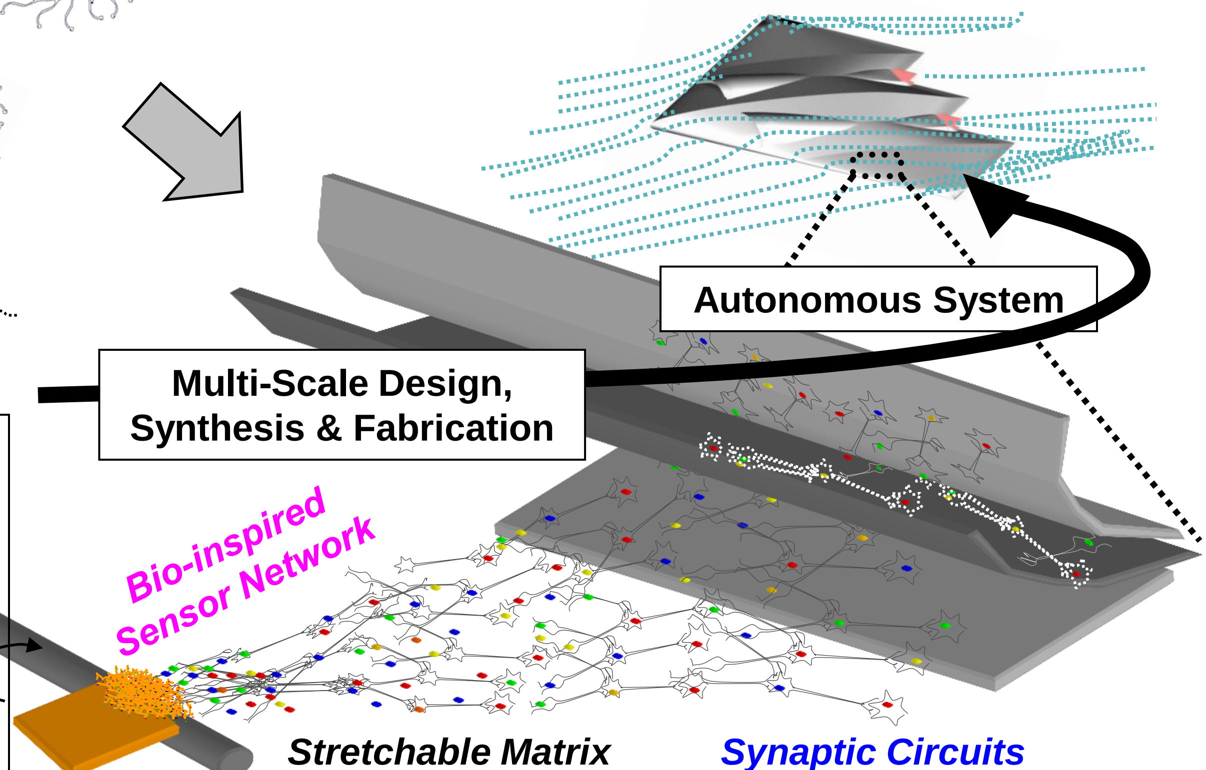
BUILT-IN SENSING NETWORK
(*Stanford/UC/DU/UCLA: Chang et al*)

MURI '09



Synapse:

Cognition and decision-making are determined by a relative level of cumulative signal strength with respect to the synapse threshold values

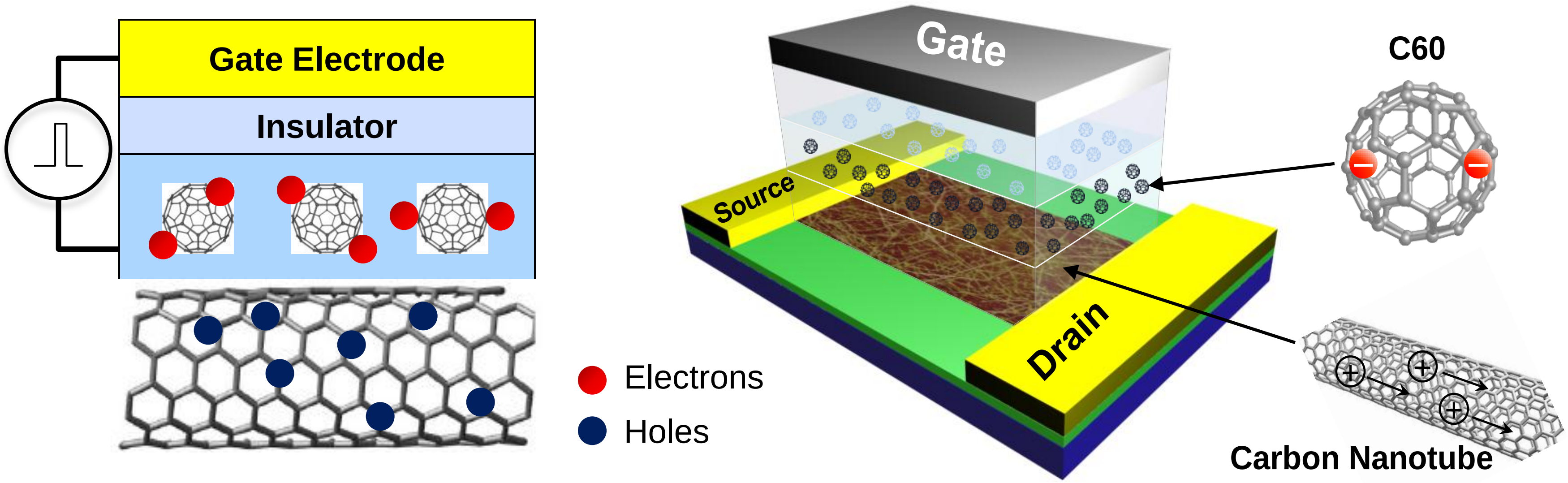


Biological sensory systems rely on large numbers of sensors distributed over large areas and are specialized to detect and process a large number of stimuli. These systems are also capable to self-organize and are damage tolerant.

PM: **B. L. Lee*; Co-PM:* Hugh Delong**

MURI ‘09

EMULATING BIOLOGICAL SYNAPSE *(UCLA: Chen) - Update*



- The 2nd generation device emulating a **biological synapse**, which integrates spatiotemporal logic, memory and learning functions, has been developed by integrating **CNT’s** and **C60-doped polymer** layer in a **field-effect transistor**. This novel “**synapstor**” offers drastically reduced power consumption compared to Si CMOS transistors.
- A voltage pulse applied on the gate of a synaptic transistor triggers electronic charge/discharge in the C60 molecules in the polymer to generate **post-synaptic current** (PSC).
- The amplitudes of the post-synaptic current can be **configured to analog states** quantitatively (ranging from 10^-12 to 10^-7 A) and **reversibly** by modifying the charge inside the C60 molecules with a series of gate pulses.
- Based on the extrapolations of the experimental data, the analog values could be distinguished and preserved for years, indicating the **long-term nonvolatile analog memory** of the synapstor.

PORTFOLIO OVERVIEW

NAME: *B. L. ("Les") Lee*

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging mater
into future Air Force systems requiring multi-fur

LIST OF SUB-AREAS:

- *Design of Autonomic/Self-Sustaining System*
- *Design of Reconfigurable Systems;*

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Self-Diagnosis;
Self-Healing, Remediation & Structural Regener
Self-Cooling & Thermal/Irradiation Management,
Energy Transduction & System Integration;
Actuation, Morphing & Threat Neutralization;
Engineered Bio/Nano/Info-materials

***PI's** & Co-PI's:*

John Kieffer (U Mich)
Ioannis Chasiotis (UIUC)
Jerry Qi (U CO)
Kurt Maute (U CO)
Martin Dunn (U CO)
G. Ravichandran (Caltech)*
*Jose Andrade (Caltech)**
*Kaushik Bhattacharya (Caltech)**
*Chiara Daraio (Caltech)**
*Michael Ortiz (Caltech)**
*Chris Lynch (UCLA)**
*Greg Carman (UCLA)**
Naresh Thadhani (GA Tech)
Sarah Stewart (Harvard U)
John Borg (Marquette U)

*** CoE**

PORTFOLIO OVERVIEW

NAME: *B. L*

BRIEF DES

Basic scie

into future

LIST OF SU

- *Design*
- *Design*

Fundamen

Life Predic

Sensing, D

Self-Healin

Self-Coolir

Energy Tra

Actuation,

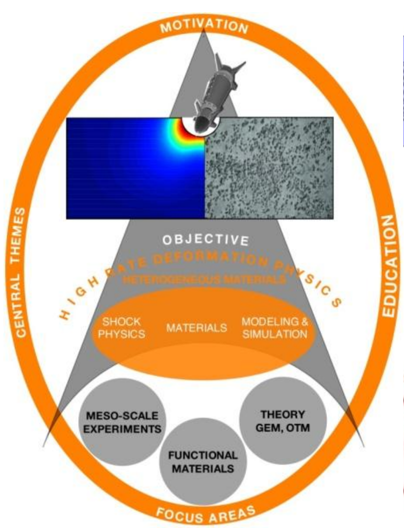
Engineere

***Subject*:**	***PI's** & Co-PI's:*
<< Multi-scale Simulation of Interfacial Phenomena	***John Kieffer (U Mich)***
<< Deformation & Fracture of Silicon for MEMS	***Ioannis Chasiotis (UIUC)***
>> 3D Printed Composites for Topology Transform	***Jerry Qi (U CO)***
	Kurt Maute (U CO)
	Martin Dunn (U CO)
High-rate Physics of Heterogeneous Materials	***G. Ravichandran (Caltech)****
	*Jose Andrade (Caltech)**
	*Kaushik Bhattacharya (Caltech)**
	*Chiara Daraio (Caltech)**
	*Michael Ortiz (Caltech)**
	*Chris Lynch (UCLA)**
	*Greg Carman (UCLA)**
Dynamic High-Pressure Behavior of Geomaterials	***Naresh Thadhani (GA Tech)***
	Sarah Stewart (Harvard U)
	John Borg (Marquette U)
>> New; << Concluded	**** CoE***

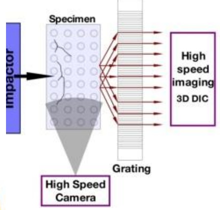
AFOSR/RW CoE'12 - SHOCK PHYSICS (Caltech/UCLA: Ravichandran)

Objectives:

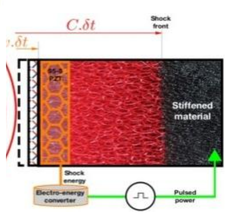
- Fundamental understanding of the **physics** of heterogeneous materials at **high-strain-rates** (10^5-10^7/s) and **high-pressures** (1-100 GPa)
- Development of **microstructures** and **functional nanomaterials** for **mitigating shock and damage**
- Use of innovative methods for **educating and training** the next generation of scientists and practitioners



Experimental shock physics

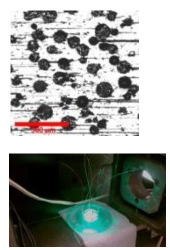


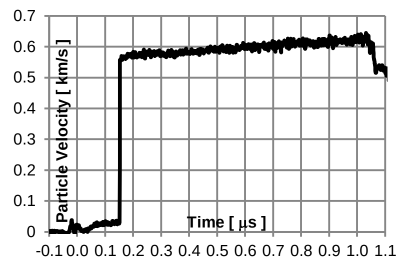
Shock mitigation



Achievements:

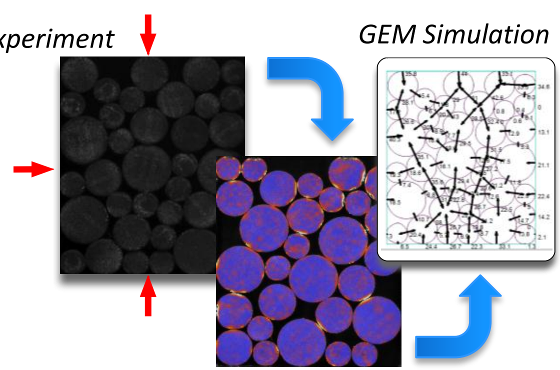
- Shock physics of **"model" particulate composite** (glass spheres embedded in PMMA).



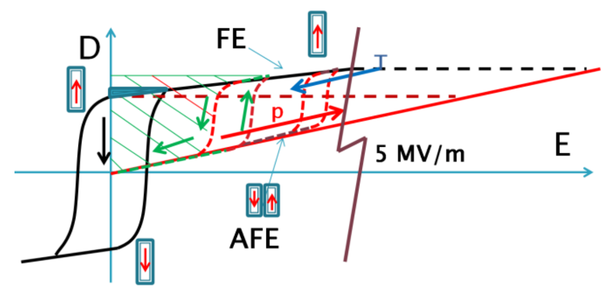


- Concept of **metaconcrete** with effective "negative" mass which can potentially trap or disperse waves generated by shock loading
- Validated Granular Element Method (**GEM**) for computing interparticle forces in a model particulate material

Experiment *GEM Simulation*



- Ferroelectric and ferromagnetic based **energy harvesting materials** for shock mitigation
  - Pressure induced depolarization in 95/5 and 52/48 PZT based compositions characterized under hydrostatic and dynamic loading (split Hopkinson bar)



Shock energy corresponding to area to left of the curve can be harvested for ferroelectrics (Similar cycle for ferromagnetics)

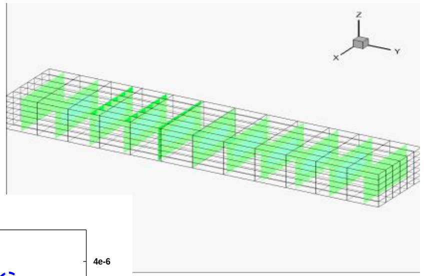
Perspectives:

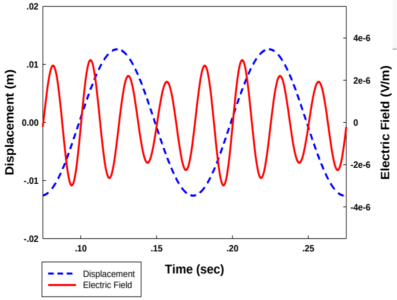
- New generation of analysis, design, simulation and experimental tools for heterogeneous material structures and systems of interest to the Air Force
- Design of robust munitions systems with novel protective systems for structures, electronics and guidance systems

COUPLING EM-STRUCTURAL DYMAMICS *(JHU: Ghosh)*

<u>Objective</u>:

To develop a comprehensive **3D multi-physics**, **multi-scale** computational analysis and simulation capability for **multi-functional composite** structures.





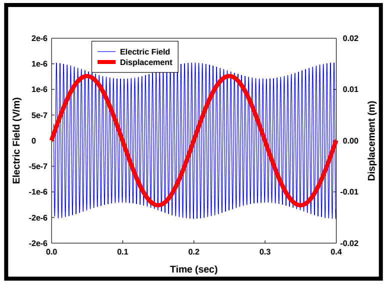
$$\frac{f_{em}}{f_{me}} = 4$$

<u>Approaches</u>:

1. Ubiquitous Multi-Physics Modeling incl. Transients: Coupled transient electromagnetic (EM) and dynamic mechanical (ME) fields

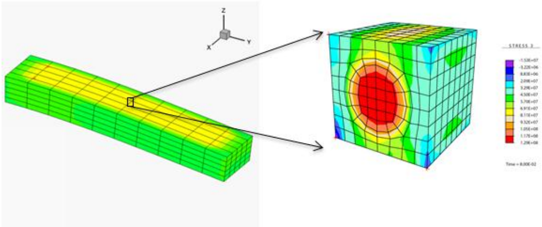
2. Temporal Multi-Scaling for Disparate Frequencies: Electromagnetics (ultrasonic frequency) and mechanical vibration (moderate frequency) in a unified modeling framework

$$\frac{f_{em}}{f_{me}} = 40$$



3. Spatial Multi-Scaling for Composite Media: Need to account for microstructure-structure interaction and design, e.g. conductors/reinforcements in antenna, conductor-substrate in sensors, and nodes (piezoelectric sensor) and wires (connection of nodes) in sensor network.

<u>Macroscopic model</u> **<u>Microscopic model</u>**



4. Piezoelectric Materials: Undergoing finite deformation

SUMMARY

- The program is fully focused on the multi-functional design of advanced aerospace materials and structures.
- A major progress has been made in pursuing a new vision for autonomic, self-sustaining and reconfigurable systems and providing basic research support for mechanics of emerging materials and micro-devices as its foundation.
- Multi-disciplinary research bases are successfully formed for *"self-healing," "structurally integrated energy harvest/storage capabilities," "load-bearing antennas"* and *"morphing materials."*
- Thee initiatives are in progress for *"neurological system inspired sensory network"* (MURI '09), *"high-rate deformation"* (CoE'12) and *"biomolecular autonomic material systems"* (BRI'12).
- New initiatives are planned for *"muscular-skeletal system inspired actuation network"* and *"structural regeneration and remodeling"* in collaboration with AFOSR/AFRL-TD/NSF colleagues.